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Proposal

# CAPTAIN-MINER$\nu$A: Neutrino-Argon Scattering in a Medium-Energy Neutrino Beam

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**Abstract**

The NuMI facility at Fermilab is currently providing an extremely intense beam of neutrinos for the NO$\nu$A, MINER$\nu$A and MINOS+ experiments. By installing the 5-ton CAPTAIN liquid argon TPC in front of the MINER$\nu$A detector in the NuMI beamline and combining the data from the CAPTAIN, MINER$\nu$A and MINOS+ detectors, a broad program of few-GeV neutrino cross section measurements on argon can be pursued. These measurements will be extremely helpful for future oscillation experiments. By directly comparing the cross sections on argon to MINER$\nu$A's scintillator (CH) target, a new level of precision can be achieved in the measurements of the effects of the nucleus on neutrino interactions. These effects are of interest to not only the particle physics but also the nuclear physics community. This document describes in detail the physics goals of the CAPTAIN-MINER$\nu$A experiment, in addition to a first estimate of the technical resources required to install, commission and operate the CAPTAIN detector in front of the MINERVA detector.

# 1 Introduction

It is well known that neutrinos propagate as a superposition of mass eigenstates and interact as flavor eigenstates, resulting in the phenomena of neutrino oscillations. Because the neutrino oscillation probability is energy-dependent, reconstruction of the incoming neutrino energy is critical. Experiments that study neutrino oscillations must reconstruct the neutrino energy based only on the final state particles. Therefore, precision measurements of neutrino cross sections and nuclear effects are needed in order to have a complete understanding of neutrino oscillations. Fermilab will host the Long-Baseline Neutrino Facility (LBNF), which will provide a high-power, wide-band muon neutrino beam for DUNE, the Deep Underground Neutrino Experiment, to be located at a baseline of 1300 km [1]. At that baseline, the first oscillation maximum occurs in the neutrino energy range from 1.5 to 5 GeV, and most of the electron neutrino appearance signal will be in this energy range [2]. DUNE has proposed to use a liquid argon time project chamber (TPC) detector, and therefore measurements of neutrino-argon interactions in this energy range are crucial for the success of the long-baseline program. The CAPTAIN-MINER$\nu$A experiment is designed to address this issue. This paper describes a proposal to install CAPTAIN, a small liquid argon TPC, in the MINER$\nu$A detector and use the combined data set to study neutrino-argon interactions and liquid argon event reconstruction in the few-GeV neutrino energy range.

The MINER$\nu$A experiment is currently taking data in the NuMI beamline, a broadband muon neutrino beam with an energy range spanning 3-8 GeV. This energy range is ideal in that it covers the first oscillation maximum for DUNE and can provide access to both elastic and inelastic processes. The MINER$\nu$A detector consists of a series of nuclear targets followed by a fine-grained scintillator tracking region surrounded by electromagnetic and hadronic calorimeters. The magnetized MINOS near detector (ND) serves as a downstream muon spectrometer. MINER$\nu$A's dataset includes interactions on a variety of nuclei ranging from helium to lead. The high intensity of the beam means that with the planned neutrino and antineutrino beam exposure, MINER$\nu$A will collect several million neutrino charged current (CC) interactions and expects to have the statistics to measure cross section ratios between graphite, iron, lead and the plastic scintillator from intermediate to high $x_{Bjorken}$ at the few percent level. The fine granularity of the MINER$\nu$A detector can also provide cross section ratios for individual neutrino interaction channels, such as coherent and inclusive pion production and quasi-elastic scattering.

CAPTAIN (Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos) is a liquid argon TPC currently being built at Los Alamos National Laboratory (LANL) [3]. The CAPTAIN program consists of a prototype detector, mini-CAPTAIN, and the full CAPTAIN detector. The CAPTAIN detector is a portable and evacuable cryostat that can hold 7700 liters of liquid argon. The active volume will be five tons. The CAPTAIN TPC is a hexagonal shape with a 1 m height and 2 m diameter, consisting of three active wire planes with 3 mm pitch and 3 mm wire spacing besides the cathode plane, grid plane, and ground plane. CAPTAIN will be equipped with a photon detection system to observe scintillation light produced inside the liquid argon. A laser calibration will be employed to monitor the electron lifetime and drift velocity, as well as measure the electric field in-situ. The mini-CAPTAIN detector is a smaller liquid argon TPC inside a 1500 liter cryostat. See Section 4 for more details of the CAPTAIN detector.

CAPTAIN is designed to conduct studies important for precision measurements of neutrino oscillations and observation of supernova burst neutrinos in a next-generation liquid argon neutrino detector. The first major physics run of the CAPTAIN experiment will take place at the Los Alamos Neutron Science Center (LANSCE). The neutron data will be used to measure spallation products that are backgrounds to measurements of supernova burst neutrinos, to study events that mimic the electron neutrino appearance signal in a long-baseline neutrino oscillation experiment, and for other studies relevant to supernova or long-baseline neutrino physics. After the neutron measurements, we expect to move the CAPTAIN detector to Fermilab to focus on neutrino beam measurements. One of CAPTAIN's goals is to measure neutrino-argon cross sections at a neutrino energy similar to that of supernova burst neutrinos, which could be accomplished by placing CAPTAIN in an off-axis position in the BNB [4]. The final physics goal of CAPTAIN is the one relevant to the CAPTAIN-MINER$\nu$A proposal: to study neutrino interactions in the neutrino energy range relevant for long-baseline neutrino oscillation physics.

Integrating CAPTAIN into MINER$\nu$A presents the opportunity to reconfigure the MINER$\nu$A detector while keeping with MINER$\nu$A's physics mission. Combining CAPTAIN and MINER$\nu$A is beneficial because some particles exiting CAPTAIN, most importantly forward-going muons, can be tracked and their energy measured in MINER$\nu$A and/or the MINOS ND, resulting in a far better estimate of the incoming neutrino energy than could be achieved with CAPTAIN alone. In addition, by making measurements of cross section ratios, namely argon to hydrocarbon in the scintillator, stringent tests of the nuclear effect models can be made, since these cross section ratios are not hampered by large flux uncertainties. Another advantage of integrating CAPTAIN into MINER$\nu$A is that the combined CAPTAIN-MINER$\nu$A detector could serve as a model for a DUNE near detector system. The reference design for the DUNE near detector is a fine-grained tracker detector designed to make precision measurements of the neutrino flux, cross sections, and signal and background rates. One enhancement to the reference design under consideration is the addition of a liquid argon TPC upstream of the fine-grained tracker to be used for a relative measurement with identical near and far detector technology.

The simplest way to integrate the CAPTAIN detector into MINER$\nu$A is to replace MINER$\nu$A's existing liquid helium target with the CAPTAIN detector, and this is our default plan. Depending on the timing of the run, it might also be possible to remove MINER$\nu$A's nuclear targets and some of the scintillator planes from the tracking region to place CAPTAIN closer to the MINOS ND, resulting in better muon acceptance. This second option would only be considered once MINER$\nu$A has collected sufficient statistics to fulfill its physics goals in the NuMI antineutrino beam mode.

# 2 Physics Motivation

## 2.1 Liquid Argon TPC R&D

The data taken by CAPTAIN-MINER$\nu$A can be used to validate the liquid argon detector technology in a neutrino beam similar to that which will be used in the long-baseline program. The capabilities for exclusive particle reconstruction and identification and shower reconstruction will be assessed.

Results on neutrino-argon interactions [5, 6, 7, 8] have been released from ArgoNeuT, a 170 liter (0.25 ton active volume) liquid argon TPC that took data in the NuMI low-energy beam configuration. However these results are statistically limited. With a fiducial mass approximately 20 times larger than that of ArgoNeuT, CAPTAIN will collect significantly more events and have better containment of the final state particles. Furthermore, cross section ratio measurements (argon to hydrocarbon) are available given the placement of CAPTAIN in front of MINER$\nu$A.

Liquid argon TPCs provide excellent position resolution, energy resolution, and particle identification, enabling precision reconstruction of complex interaction topologies. Figure 1 shows one event collected by the ArgoNeuT detector [9] in the NuMI beam. The individual particle tracks and location of the vertex are easily discernible. Events in the CAPTAIN detector are expected to be of the same high quality, making CAPTAIN a very capable vertex detector for CAPTAIN-MINER$\nu$A.

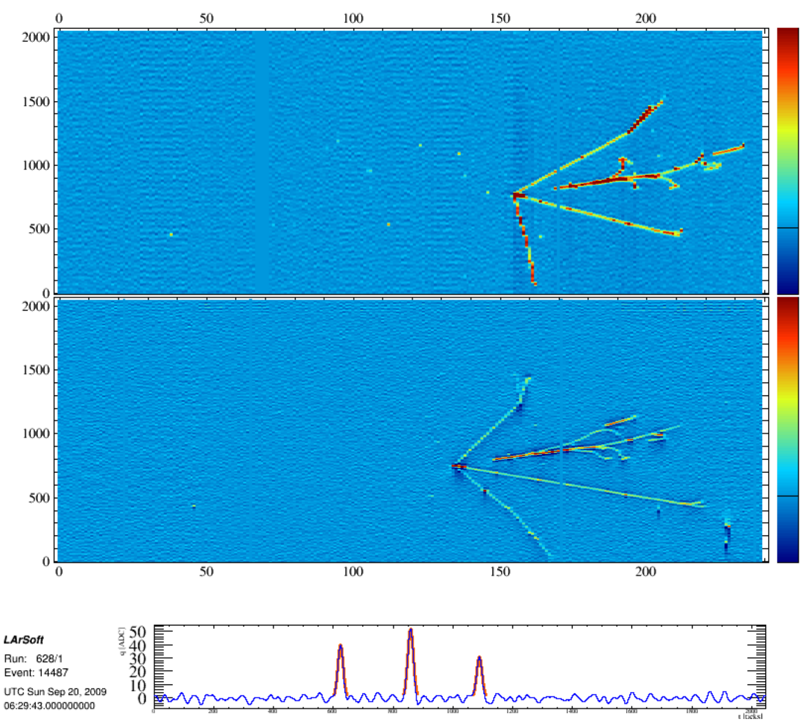



Figure 1: An event display from a real event in the ArgoNeuT detector [9]. The image depicts both the Collection (top) and Induction (bottom) plane views. The horizontal axis corresponds to the wire number within a plane, while the vertical axis corresponds to the sampling time (which is equivalent to the distance along the drift direction). The color-scale depicts the amplitude of the ADC pulse on a wire.

MicroBooNE [10, 11], a 170-ton liquid argon TPC (∼100-ton active volume) which recently completed construction at Fermilab, will study neutrino interactions on argon in the Booster Neutrino Beam (BNB) at Fermilab. The BNB has a peak neutrino energy $\mathcal{O}$(1 GeV), consistent with the energy range of the second oscillation maximum for a baseline of 1300 km. Thus measurements made by CAPTAIN in the NuMI beam are complementary to the low-energy neutrino measurements that will be made by MicroBooNE in the BNB. Figure 2 compares the neutrino flux from the medium-energy NuMI beam at the MINOS near hall, the flux from the BNB at the location of MiniBooNE, and the proposed flux for DUNE at the DUNE far detector. The NuMI beam overlaps the entire neutrino energy range for DUNE, though the NuMI beam peaks at a higher neutrino energy. The fact that the CAPTAIN-MINER$\nu$A experiment will actually have a different incoming neutrino spectrum than the DUNE far detector is also an advantage in that it will allow a cross check on the modeling of the convolution of energy-dependent cross sections and energy-dependent nuclear effects in neutrino-argon interactions made with the DUNE near detector. Figure 2 also shows the cross section for CC neutrino-argon interactions, which are dominated by pion production and Deep Inelastic Scattering (DIS), as defined by the neutrino event generator GENIE[2] [12], in the energy range relevant for DUNE. Simulations indicate that approximately 68% of all CC neutrino interactions in CAPTAIN-MINER$\nu$A will have at least one pion in the final state; in MicroBooNE, approximately 60% of the interactions will be quasi-elastic. Therefore CAPTAIN-MINER$\nu$A will have the unique ability to study event reconstruction for a large sample of neutrino events with significant particle multiplicities.

## 2.2 Physics Issues

### 2.2.1 Relationship to the Long-Baseline Program

Recent neutrino oscillation results have shown that one of the main systematic uncertainties is the uncertainty of the neutrino interaction model used to predict the neutrino interaction rate. Even in the case of a carbon target, the uncertainties are rather large despite the number of recent cross section measurements by MiniBooNE, MINER$\nu$A, and T2K. On the theoretical side there are, in some cases, large differences in theoretical foundation between models describing equally well the same experimental results. There is a consensus that more and precise neutrino cross section measurements are needed to constrain the theoretical models.

[2]Elsewhere in this document we will use the kinematic definition of DIS with $W > 2$ GeV, rather than the GENIE definition.

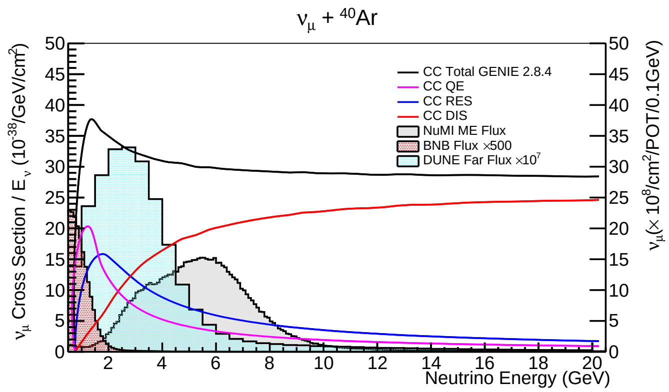



Figure 2: Unoscillated $\nu_\mu$ DUNE far flux, BNB flux at MiniBooNE, medium-energy NuMI flux at the MINOS near hall and GENIE cross section on $^{40}$Ar.

In contrast, there are only few cross section measurements for argon (those by ArgoNeuT), the neutrino target for DUNE. The goal of DUNE will be to perform precise measurements of the neutrino oscillation parameters. This requires the precise knowledge of the neutrino interaction cross sections and nuclear effects in order to predict both signal and background rates in the far detector. DUNE will employ near and far detectors which is a standard setup for long-baseline neutrino oscillation experiments with the purpose of reducing the flux and cross section systematic uncertainties. Before predicting an incoming neutrino energy spectrum in the far detector, the measured near detector spectrum must be corrected with the neutrino interaction model to get the incoming (before nuclear effects) neutrino spectrum at the near detector position. This corrected spectrum is then what oscillates into an incoming neutrino energy spectrum in the far detector. The interaction model is then necessary again to convert the incoming neutrino spectrum at the far detector into an expected measured spectrum. Since the energy spectrum of incoming neutrinos at the far detector will be different than at the near detector, different convolutions of the energy-dependent cross sections and energy-dependent nuclear effects will be involved in the near and far detectors; there is no direct cancellation. Therefore, having a reliable neutrino interaction model is key for the success of DUNE. Models in modern neutrino generators are constrained by available neutrino and charged lepton data. These include data on various targets including hydrogen, deuterium, iron, lead, water, mineral oil, plastic scintillator, etc. Charged lepton data is used to constrain the vector current while the neutrino data is used to constrain the axial part of the interaction. In addition, pion scattering data is used to constrain the final state interactions (FSI). Given the lack of precise nuclear cross section ratios above and below argon, it has not been demonstrated that existing cross section models can be reliably extrapolated for scattering on argon. The CAPTAIN detector exposed to the NuMI neutrino beam at Fermilab can be used to map out the phase space of neutrino interactions on argon for energies covering the first oscillation maximum for DUNE. A summary of existing data and theoretical models follows.

### 2.2.2 Existing Data

The energy range of DUNE overlaps a variety of experiments. For neutrino probes, MiniBooNE has published a number of interesting results for $CH_2$ at $\langle E_\nu \rangle \sim 1$ GeV [13, 14]. T2K will add many results for CH and $H_2O$ in the near future. At higher energies ($\langle E_\nu \rangle \sim 4$ GeV), MINER$\nu$A has published a few results for CH, Fe, and Pb targets with the NuMI low energy (LE) beam [15, 16, 17] and many more are in progress [18]. ArgoNeuT is starting to publish results for Ar with the same beam as MINER$\nu$A, and NOMAD [19] has a set of results at higher energies. These experiments give results for quasielastic (QE), pion production, coherent, and inclusive interactions. Electron scattering has a wide range of data for inclusive interactions, $(e, e'X)$, for many targets and beam energies. Typical targets of interest for Ar experiments include C, Ca, and Fe including a small data set for Ar. There is a smaller body of data for $(e, e'p)$ and some very new results for $(e, e'pp)$. A new experiment will take $(e, e'p)$ data for an Ar target soon [20].

Electron scattering experiments study the vector interaction, i.e. photon exchange, with great accuracy and specificity. The beam energy is fixed and absolute cross sections with few percent accuracy are standard. Experiments to date have emphasized the electron in coincidence with 0-2 hadrons using narrow or wide range spectrometers. Neutrino experiments study a combination of vector and axial vector (i.e. $W^\pm, Z^0$) exchange interactions. They use a wide-band beam with $\sim 1$ GeV width and absolutely normalized results require extensive efforts because the beam is difficult to monitor. In contrast to electron experiments, the neutrino target and detector are almost always identical and the solid angle is then very large (including final state particles at a lab angle of $0°$ which is impossible in most experiments). The electron experiments are important to establish nuclear models and FSI of particular particles, but give minimal information about the complex final states neutrino experiments need to understand to accurately measure the neutrino energy.

Event generator Monte Carlo programs must use both kinds of information. The general strategy is to use conserved vector current (CVC) symmetry to transform the electron scattering results into the vector contribution for neutrino scattering. A theoretical model is then used for the axial vector part of the neutrino interaction and the combined model is compared to actual neutrino scattering data. Hadron beam data provide the information for FSI of the hadrons produced in neutrino experiments. Thus, electron and hadron beam experiments have a key role in the prediction of neutrino interactions.

Putting together these disparate pieces of information within existing models is a very difficult task. Estimates of uncertainties associated with these methods are very important but necessarily imperfect. The first priority is to get more and better neutrino data to test extrapolations of nuclear effects to nuclei heavier than argon, and the second priority is to minimize the extrapolations by making measurements on argon in the DUNE energy range.

### 2.2.3 Examples of Present Data and Model Problems

**Pion Production and FSI from Δ Resonance Excitation** One of the most important final states is inclusive one-pion production. This is an important component of the DUNE first oscillation maximum. The theory for electromagnetic probes is well established from interpretations of pion and photon data. The medium effects of the $\Delta$ are known to change cross sections by roughly 20%. Theorists then apply the same models to neutrino data, adding the weak interaction in an analogous fashion.

The MiniBooNE data [13] set a new standard for high quality. The BNB is well understood and the statistics are very high. Although they supply double differential cross sections in e.g. pion energy and angle, the most interesting spectrum has turned out to be the one dimensional pion energy spectrum. Since this spectrum overlaps the pion energies coming from the full width of the $\Delta(1232)$ resonance, a strong FSI effect is expected with the strongest suppression at $T_\pi \sim 160$ MeV where the $\pi^+$C cross section peaks. Rodrigues [21] reported comparisons with theoretical calculations and event generator results. The surprising result was that none of the calculations were in good agreement and the best theoretical calculations (GiBUU [22] and Valencia [23]) had the poorest match to the data. The conclusion is that either the pion beam data is not the proper way to build an FSI model or that the models are wrong.

The MINER$\nu$A data [18] has a significant overlap with the MiniBooNE kinematics; they present both energy and angle spectra for events where $W < 1.4$ GeV. This focuses on events where a $\Delta(1232)$ resonance was created at the principal vertex. The newer data shows that the pion energy spectrum is more valuable than the angle spectrum. Like MiniBooNE, there is no dip at the peak of the resonance. Some calculations (NuWro [24], NEUT [25]) are in good agreement while others (GENIE [12], GiBUU [26]) have the right shape but the wrong absolute magnitude. Equality of the MINER$\nu$A and MiniBooNE cross sections for high energy pions ($T_\pi > 300$ MeV) despite the significant difference in average neutrino energy strongly implies a problem with relative normalization of the two experiments.

This is the odd situation where two experiments don't have a common interpretation. Calculations have different problems in describing each data set. Oscillation experiments are forced to cope with this and application of significant systematic uncertainties is the expected result.

**Pion Production at Higher Mass** For higher $W$, behavior of higher energy pions with higher multiplicity is studied. The reaction mechanism is more complicated and the kinematical region 1.4 GeV $< W <$ 2.0 GeV is called the transition region. It sits between resonance-dominated and DIS regions and shares characteristics of each of them. There is a wealth of data from electron experiments for a wide range of kinematics and targets. For nuclear targets, $(e, e')$ data is most important although a new result for inclusive pion electroproduction at JLAB is expected soon. For nucleon targets, the $\Delta$ excitation dominates at $Q^2 <\sim 1$ GeV$^2$. At higher $W$, a tower of the higher mass resonances is seen but nonresonant mechanisms of comparable strength are also present. Similar behavior is seen in the low statistics deuterium bubble chamber data with neutrino probes. Above $W > 1.8$ GeV, empirical approaches such as KNO [27] become appropriate. This is the model chosen in GENIE [28]. There is very little neutrino data for nuclear targets for this range of excitation. Although older data has been valuable for model development, new MINER$\nu$A data with the medium-energy NuMI beam will be a much-needed addition.

**Deep Inelastic Processes** At even higher excitation energies $W > 2$ GeV, the relevant processes come from interactions with the quarks in the target. DIS accounts for about a third of all neutrino interactions at the neutrino energy of the first oscillation maximum for DUNE and becomes the dominant interaction channel at neutrino energies above 5 GeV. DIS has been measured on various targets with high precision for neutrino energies greater than 10 GeV. In this region the neutrino DIS cross section has been measured on carbon, iron and lead targets with a precision better than 4% by the CDHS [29], NuTeV [30], NOMAD [31], and CHORUS [32] experiments. At these energies most of the phase space is in the regime of perturbative QCD. Higher order corrections like target mass effects and higher twist are needed at high $x_{Bjorken}$ and low $Q^2$. The Bodek-Yang [33] model is used to simulate neutrino DIS events in modern neutrino generators. This model is based on the leading order parton distribution functions (PDF) for the quark densities in a free nucleon, and includes next-to-leading order corrections. The free nucleon PDFs are obtained from a global fit to the charged lepton DIS data. GENIE uses a hadronization model to predict the multiplicity of the initial state. This model is tuned to the existing multiplicity data and bubble chamber data. The hadronization model also includes heavy quark production. Final state interactions modify the multiplicities for scattering on nuclei. Nuclear effects have been measured by charged lepton DIS experiments with high precision. However, data from NuTeV and CHORUS suggests differences between neutrino and charged lepton DIS due to the axial-vector current and to flavor selection which results in almost no enhancement in the shadowing region (small $x_{Bjorken}$) for neutrino scattering. The MINER$\nu$A experiment will measure the nuclear dependence for neutrino and antineutrino DIS as ratios to carbon Fe/C and Pb/C. In the energy region $E_\nu < 10$ GeV and $W < 4$ GeV the majority of DIS events have low multiplicity which is then modified by FSIs. In this part of phase space the coverage by existing data is poor which results in higher systematic uncertainties on the hadronization model. MINER$\nu$A will measure the neutrino and antineutrino DIS cross sections in this region on C, Fe and Pb.

### 2.2.4 What do we know about neutrino-argon interactions?

The $\nu$-nucleus interaction is very weak. Therefore, the principal interaction of the neutrino should occur according to the density of the target nucleons. The total CC cross section is proportional to the sum of the interactions with the constituents. For example, Fe and C total CC cross sections divided by $A$ are often plotted together; the Fe cross sections get an isoscalar correction of a few percent. On the other hand, the remainder of each event is dictated by strong interactions which have a mean free path of a few fm or less. These interactions have important energy dependence due to the $\Delta(1232)$ nucleon resonance having a very important role in many studies. The hadron-nucleus total reaction cross section depends on $A^{\frac{2}{3}}$ and the FSI make important modifications to the simple picture. Depending on the variable examined, the $A$ dependence varies significantly. Final states involving pion production will scale more like $A^{\frac{2}{3}}$, but we need data to know for sure. Events from Ar will have the energy from the principal interaction divided in more ways, higher multiplicity and more low energy nucleons, which will provide a challenge to any detector. In addition, the target constituents have properties that are modified by the nuclear environment. Impulse approximation (neutrino interacts with a single nucleon) prediction for the total QE cross section at $\langle E_\nu \rangle \sim 1$ GeV are well below the MiniBooNE data. The leading explanation is that the neutrino sometimes interacts with correlated nucleons. Theoreticians predict this component of the total cross section is not proportional to $A$, but support from data is not well established. At higher energies, the EMC effect shows that dividing the total cross section into bins of $x$ shows regions where different physics processes are important and the Fe and $^2$H data don't have simple scaling.

$\nu$-nucleus interaction event generators (e.g. GENIE, NuWro, and NEUT) incorporate models for all these processes. Although these models are simplified versions of the leading theoretical models, this allows predictions for all processes at all energies for all nuclei. At this time, they rely on the impulse approximation for all interactions and the Fermi Gas nuclear model. However, the model developers have had a lot of interaction with theorists to gain access to more sophisticated models. These are now going into the codes.

Therefore, event generator predictions for $\nu$Ar are based on interpolations and extrapolations of simplified models. Because of the simple scaling effects described above, basic quantities are nevertheless consistently predicted with moderate accuracy. Although the effect of these approximations is sometimes known and able to be incorporated into a systematic uncertainty, there are notable exceptions, as seen in the examples in the previous subsection. The interplay of data and model remains an interesting subject.

Although the accuracy of any prediction depends on many factors, a rough guide comes primarily from the quality of underlying data and models. The total CC cross section for $\nu$Ar can be reliably predicted. On the other hand, detailed information such as neutral energy and proton multiplicity distributions will prove to be more difficult.

The generator studies at the NUINT conferences have studied consistency among models. The NUINT09 study [34] showed wide variations in some cases and surprising agreement in others. The predictions for the pion kinetic energy distribution in single pion production from $\nu_\mu$C at 1 GeV (See Fig. 3 left) showed wide variation due to many effects. Predictions for the total CCQE cross section for $\nu_\mu$C (See Fig. 3 right) are all in agreement because the impulse approximation and the Llewellyn-Smith $\nu_\mu N$ interaction were used by all models. Confrontation with MiniBooNE data showed all were wrong. On the other hand, more detailed distributions such as the proton kinetic energy showed wide variations. These predictions were before the release of the MiniBooNE data. Some models were then tuned to the data and others remain in disagreement with it.

At NUINT12, studies were suggested by experimental collaborations, and $\nu_\mu$Ar studies as preparation for DUNE were prominent. Fig. 4 shows two results [35] from that study, both for $\nu_\mu$Ar for 3 GeV neutrinos. The proton multiplicity shows the end result of various principal interactions followed by FSI. The total visible energy sums

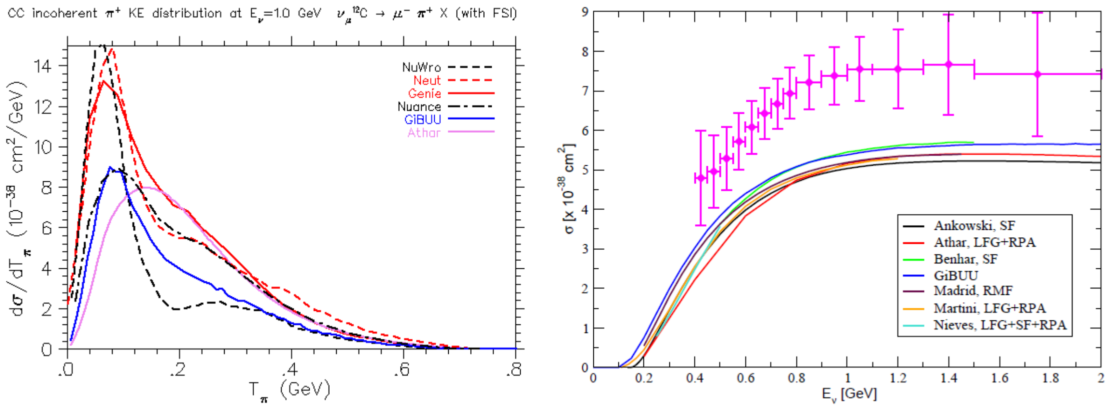



Figure 3: Results of the NUINT09 theory study [34]. Left: Pion kinetic energy cross section for 1 Gev $\nu_\mu$C from various generators. Right: Predictions for CCQE total cross section for $\nu_\mu$C. Data comes from MiniBooNE and authors of the calculations are shown. This was before the realization that nucleon correlations (commonly called MEC or *npnh*) can have significant contribution. Figure was constructed by Luis Alvarez-Ruso using the NUINT09 theory study.

total energies of lepton and mesons and kinetic energy of protons. The significant differences would bring problems for any DUNE analysis as this is a key ingredient in measurement of the incident neutrino energy. Any deviation from 3 GeV must be measured via neutral particles or come from the simulation.

We see that event generators will always be behind theoretical understanding and theoretical understanding will always be behind experiment. At the same time, predictions from theory based on results from other probes sometimes anticipate experimental results. Although we expect qualitative agreement in the key quantities from existing event generators, that is not sufficient for assessing the needs for precision experiments such as DUNE now in the planning stages. The CAPTAIN-MINER$\nu$A experiment will allow the most accurate tuning of event generators for the best DUNE performance.

## 2.3 Expected Performance

We performed simulations of neutrino interactions on liquid argon with the CAPTAIN detector geometry placed in the MINOS hall upstream of the MINER$\nu$A detector with the on-axis medium-energy (ME) NuMI flux. The simulations predict 12.5M $\nu_\mu$ CC interactions within the TPC fiducial volume for an exposure of $6\times10^{20}$

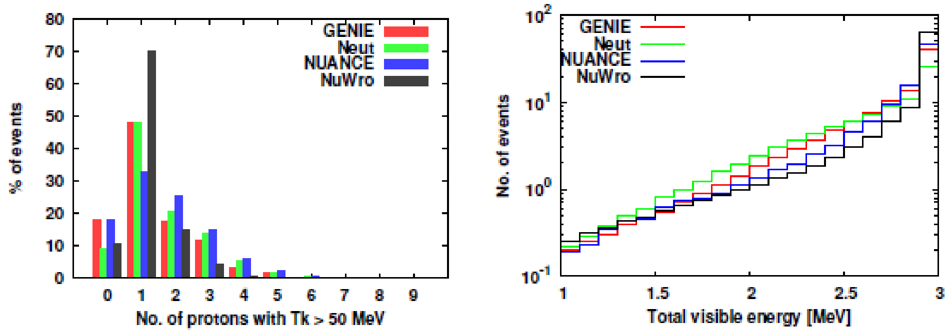



Figure 4: Predictions of various event generators for $\nu_\mu Ar$ for 3 GeV neutrino beam energy from the NUINT12 study [35]. Left: Proton multiplicity for proton kinetic energy greater than 50 MeV. Right: Total visible energy.

protons-on-target (POT). To study the acceptance of $\nu_\mu$ CC events in MINER$\nu$A and the MINOS ND, neutrino interactions were generated within the TPC fiducial volume using GENIE 2.8.4. MINER$\nu$A's detector response is simulated with a tuned GEANT4-based [36, 37] program. The MINOS ND is located 2 m downstream of the MINER$\nu$A detector. The magnetized MINOS ND can provide measurements of muon momentum and the sign of the muon charge for events where the muon reaches the MINOS ND. This matching criterion is based on a muon that exits CAPTAIN, exits the back of the MINER$\nu$A detector and reaches the MINOS ND. If the muon is reconstructed in the MINOS ND, the muon momentum is measured by the MINOS ND from the track curvature or its range depending on whether the muon stops in the detector. A detailed study by MINER$\nu$A shows that the total momentum uncertainty for muons is 2-3% for the curvature-based measurement relative to the range-based measurement [38]. For events where the muon does not reach the MINOS ND, the MINER$\nu$A detector can provide a reconstructed muon track, but not the sign of the muon charge. Figure 5 (left) shows the incoming neutrino energy distribution for $\nu_\mu$ CC interactions in the CAPTAIN TPC in the ME NuMI configuration. On the right, the muon angle with respect to the neutrino beam direction is shown for all CC events, CC events in which the muon reaches the MINOS ND, and CC events in which the muon reaches only the MINER$\nu$A detector.

By considering muons that reach MINER$\nu$A or the MINOS ND, the overall muon reconstruction efficiency for $\nu_\mu$ CC events is 64%. (23% of CC interactions have a muon reconstructed by MINOS, and 41% of CC interactions have a muon reconstructed by MINER$\nu$A.) For the remaining CC interactions, CAPTAIN will have some ability to tag muons that miss MINER$\nu$A or MINOS by looking for MIP-

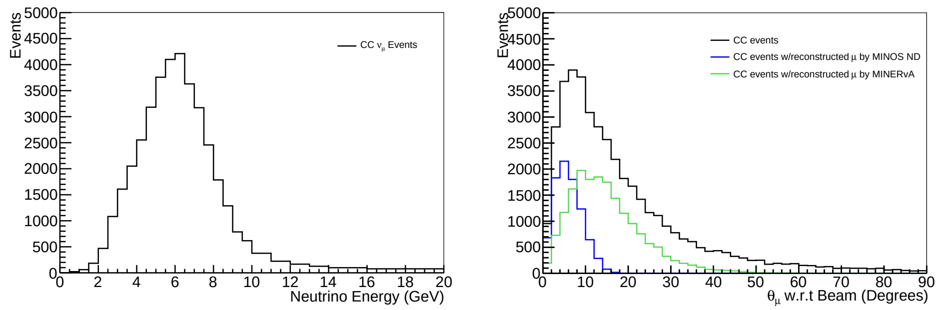



Figure 5: Left: Incoming neutrino energy for $\nu_\mu$ CC interactions in the CAPTAIN TPC in the NuMI ME flux configuration. Right: Muon angle with respect to the neutrino beam direction for all CC events (black), CC events with a muon reconstructed by the MINOS ND (blue), and CC events with a muon reconstructed by MINER$\nu$A (green).

like tracks. Figure 6 shows the muon acceptance as a function of neutrino energy, muon momentum, $Q^2$ and muon angle with respect to the beam direction. In addition, Figure 6 shows the events where the muon charge sign is reconstructed; this is particularly important for an antineutrino flux configuration to avoid wrong sign contamination. To increase the acceptance for events where the muon charge is reconstructed the CAPTAIN detector could be placed upstream of the MINER$\nu$A tracker region by removing MINER$\nu$A's nuclear targets.

Reconstructing the incoming neutrino energy is crucial in order to measure oscillation parameters. One of the key factors in neutrino energy reconstruction is detector containment. We define an event as fully contained if the neutrino interaction vertex is inside of the TPC fiducial volume and all primary particles have an end point inside of the TPC fiducial volume. Particles excluded from this requirement include muons, neutrons and neutrinos. Approximately 20% of $\nu_\mu$ CC interactions will have all the hadronic energy contained within the TPC. Given the muon reconstruction efficiency of 64%, roughly 10-15% of $\nu_\mu$ CC events will have a muon reconstructed by MINER$\nu$A or MINOS *and* all the hadronic energy contained within the TPC fiducial volume. This subset of events will have the best reconstructed energy resolution. By placing the CAPTAIN detector upstream of the MINER$\nu$A detector, MINER$\nu$A can be used as a calorimeter for events where final state particles (FSP) exit CAPTAIN and reach MINER$\nu$A. Figure 7 (left) shows an event display of a interaction in the TPC fiducial volume where a muon and two hadrons exit CAPTAIN. From the event display, we can see that the hadronic system is fully contained in MINER$\nu$A. For

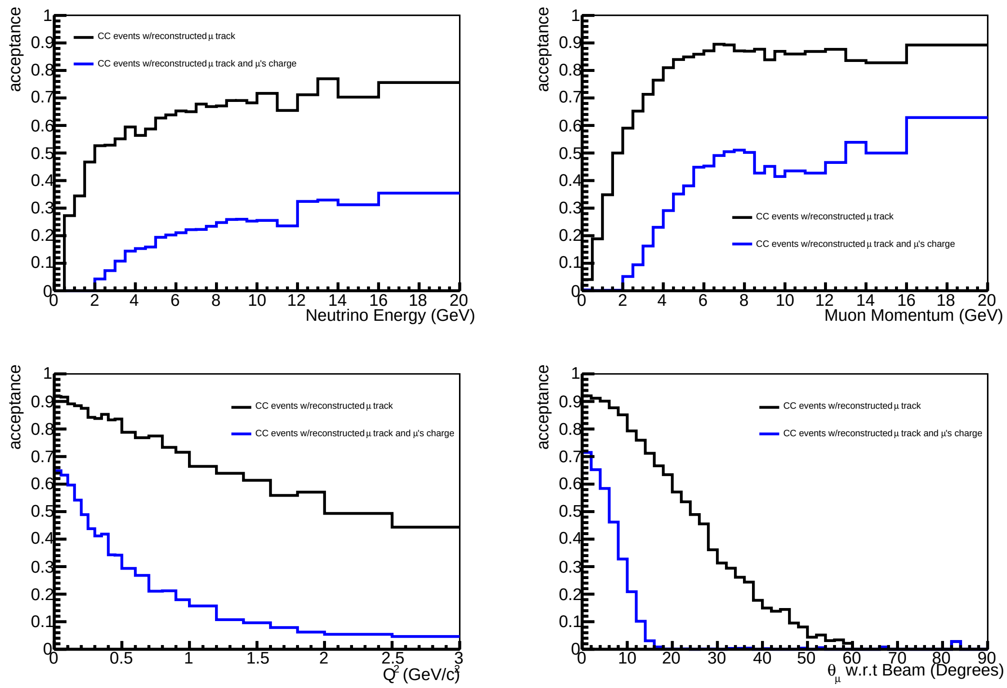



Figure 6: Muon acceptance for $\nu_\mu$ CC events as function of neutrino energy, muon momentum, $Q^2$ and muon angle with respect to the beam direction for all events with a reconstructed muon track (black) and for the subset of events with reconstructed tracks in which the charge sign is also reconstructed (blue).

events where FSP exit CAPTAIN, the fraction of visible energy that is deposited in MINER$\nu$A is shown in Figure 7 (right).

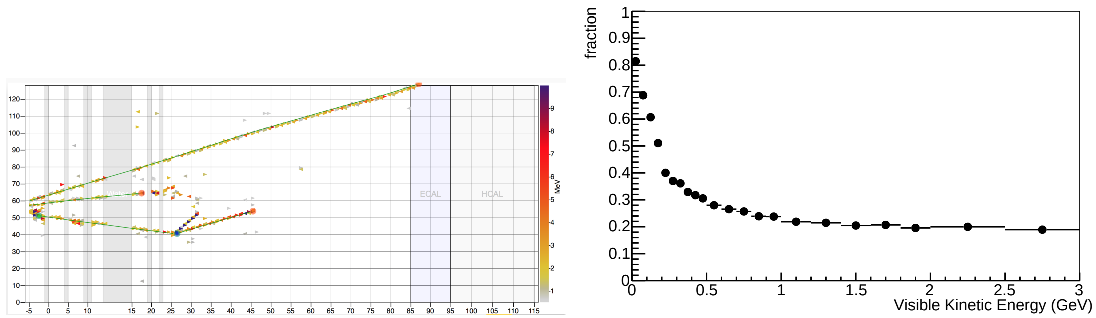



Figure 7: Left: MINER$\nu$A event display for a neutrino interaction on liquid argon upstream of the MINER$\nu$A detector. Right: Fraction of visible energy deposited in MINER$\nu$A for events where FSP exit CAPTAIN and reach the MINER$\nu$A detector.

Table 1 shows the expected event rate for CCQE-like events ($\nu_\mu + {}^{40}Ar \rightarrow \mu^- + Np$ and no mesons, $N$ can be any number of protons), CC $1\pi^\pm$ ($\nu_\mu + {}^{40}Ar \rightarrow \mu^- + \pi^\pm + X$) and CC $1\pi^0$ ($\nu_\mu + {}^{40}Ar \rightarrow \mu^- + \pi^0 + X$) assuming a $6{\times}10^{20}$ POT exposure.

| | Events w/ reco $\mu$ | Events w/ reco $\mu$ and charge |
|---|---|---|
| CCQE-like | 916k | 784k |
| CC$1\pi^\pm$ | 1953k | 966k |
| CC$1\pi^0$ | 1553k | 597k |

Table 1: Event rates for all CC events with a reconstructed muon and and for the subset of events with reconstructed tracks in which the charge sign is also reconstructed for an exposure of $6{\times}10^{20}$ POT.

# 3 Neutrino Beam

The CAPTAIN-MINER$\nu$A program will make use of the NuMI beamline, which produces a high intensity on-axis neutrino beam peaked at about 6 GeV. The beam is created when 120 GeV protons strike a graphite target to create pions, and those pions are then focused with a two-horn system and sent to a 675 m long decay pipe.

The polarity of the horns can be either positive or negative, resulting in a 97% (94%) pure beam of neutrinos (antineutrinos) at the peak neutrino energy. The operation of changing from one polarity to the other takes less than one 8-hour shift, but is not expected to be changed frequently given the plans of other experiments using the beamline.

This beam is currently in use by the MINER$\nu$A, MINOS+, and NO$\nu$Aexperiments. At the time of this writing the NuMI medium-energy beam is operating at 450 kW and is expected to provide some $6\times10^{20}$ POT per year by 2016. The intensity of this beam means that an adequate sample of events on liquid argon could be collected with only a year of running in each of the neutrino and antineutrino configurations. Figure 8 shows the neutrino fluxes per POT as a function of energy for both modes.

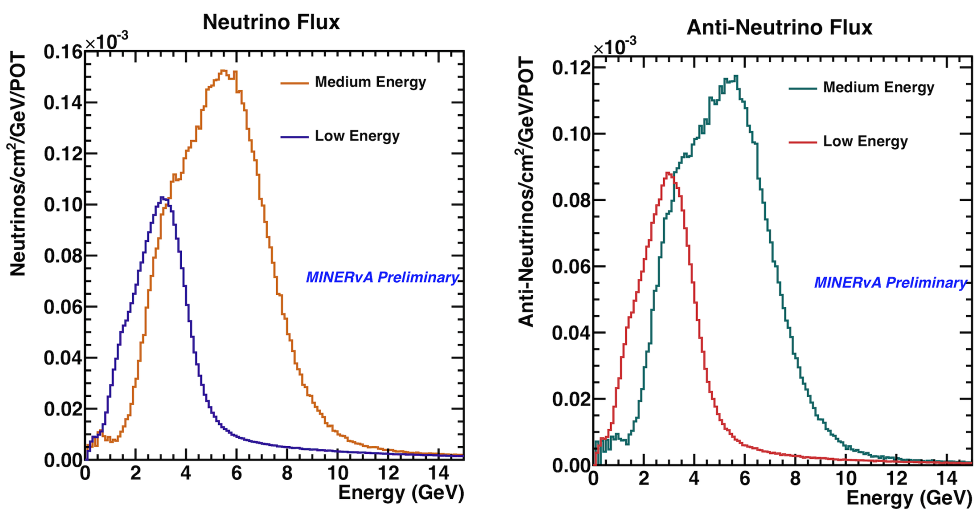



Figure 8: Neutrino (left) and antineutrino (right) fluxes per POT as a function of energy, for both the low-energy and medium-energy tunes of the NuMI beamline, as predicted by a GEANT4 simulation reweighted using results from the NA49 hadron production experiment.

The neutrino energy spectrum over the extent of the CAPTAIN detector would be roughly constant, but the CAPTAIN detector is less than 2 m wide so the detector must be placed accurately and as close to the beam axis as possible to maximize the neutrino flux. The neutrinos arrive at the detector in 10 $\mu$s spills every 1.3 s. Given the maximum drift time of 625 $\mu$s in CAPTAIN, neutrinos arriving in one beam spill can be considered simultaneous.

Because the neutrino flux demands for the NO$\nu$Aexperiment are so much higher than those of CAPTAIN-MINER$\nu$A, this proposal seeks no additional spare targets or horns above what is already planned for NO$\nu$A. We seek to measure both neutrino and antineutrino interactions on argon, and therefore, we request an exposure of at least $6 \times 10^{20}$ POT in each mode, which could be collected in a minimum of two years if timed correctly.

# 4 Detector Description and Expected Performance

## 4.1 Cryostat

The CAPTAIN cryostat is a 7700 L vacuum insulated liquid argon cryostat which will house the final TPC. It is an ASME Section VIII, Division 1 U stamped vessel making operation at several national (or international) laboratories more straightforward. The outer shell of the cryostat is 107.5 inches in diameter, and it is 115 inches tall. The vessel is designed with a thin (3/16 inch) inner vessel to minimize heat load to the argon. All instrumentation and cryogenics are made through the vessel top head. The vessel also has side ports allowing optical access to the liquid argon volume for the laser calibration system or other instrumentation. A work deck is to be mounted on the top head to provide safe worker access to the top ports of the cryostat. A baffle assembly will be included in the cold gas above the liquid argon to mitigate radiation heat transfer from the uninsulated top head. Figure 10 shows a schematic of the CAPTAIN cryostat, TPC, and work deck.

## 4.2 Cryogenics

Liquid argon serves as target and detection medium for the CAPTAIN detector. The argon must stay in the form of a stable liquid and must remain minimally contaminated by impurities such as oxygen and water. This is to prevent the loss of drifting electrons to these electronegative molecules. It must also stay sufficiently free of contaminants such as nitrogen to avoid absorption of the scintillation light.

The maximum drift distance is 100.0 cm for the full CAPTAIN detector. To achieve a sufficiently long drift-distance for electrons, the $O_2$ contamination is required to be smaller than 240 ppt for CAPTAIN. Quenching and absorption of scintillation light are demonstrated [39, 40] to be negligible when the $N_2$ contamination is smaller than 2 ppm.

The cryogenics system must receive liquid argon from a commercial vendor, test its purity, and further purify it. Cryogenic pumps and filter vessels purify the liquid in the detector by removing electronegative contaminants. Cryogenic controls monitor and regulate the state of the argon in the detector. Commercial analytic instruments are used to characterize the oxygen and water contaminant levels in the argon. The CAPTAIN liquid argon delivery and purification design is based on experiences of the MicroBooNE experiment [10, 11] and the Liquid Argon Purity Demonstration (LAPD) [41], both based at Fermilab.

The CAPTAIN TPC has a liquid argon volume of 7.5 $m^3$, which is equivalent to 6300 $m^3$ of argon gas at STP. Assuming a bulk liquid argon contamination level of $O_2$ at 1.0 ppm, this is equivalent to 8.253 grams of $O_2$ in the total volume of the detector. The current design for the vessel that will hold the two filter mediums has a total volume of $\sim$80.0 liters, or $\sim$40.0 liters for each filter material. The dual filter system consists of a bed of molecular sieve (208604-5KG Type 4A) to remove moisture and another bed of activated copper material (CU-0226 S 14 X 28) to remove oxygen. Experience from LAPD shows this should be sufficient. Both filter materials are reactivated when saturated. The molecular sieve is heated with an argon gas flow that acts as a carrier gas, removing water molecules liberated from the sieve. The copper is reactivated with a heated flow of argon gas doped with a non-flammable level of hydrogen gas that reacts with the oxygen on the copper surface.

The design utilizes a 10-12 gal/min capacity commercial centrifugal pump. Magnetic coupling prevents contamination through shaft seals. The pump will be mounted with the filter vessel on a single skid in order to achieve portability.

A sintered metal filter is used to remove dust from the liquid argon prior to its delivery to the cryovessel.

## 4.3 Electronics

The electronic components for the TPC are identical to those of the MicroBooNE experiment at FNAL [10, 11]. The front-end mother board is designed with twelve custom CMOS Application Specific Integrated Circuits (ASIC). Each ASIC reads out 16 channels from the TPC. The mother board is mounted directly on the TPC wire planes and is designed to be operated in liquid argon. The output signals from the mother board are transmitted through the cold cables to the cryostat feed-thru to the intermediate amplifier board. The intermediate amplifier is designed to drive the differential signals through long cable lengths to the 64 channel receiver ADC board. The digital signal is then processed in an FPGA on the Front End Module (FEM) board. All signals are transmitted via fiber optic from a transmit module to the data acquisition computer.

## 4.4 TPC

The TPC, shown in Figure 9, consists of a field cage in a hexagonal shape with a mesh cathode plane on the bottom of the hexagon and a series of four wire planes on the top with a mesh ground plane. The apothem of the TPC is 100 cm and the drift length between the anode and cathode is 100 cm. In the direction of the electron drift, there are four wire planes. In order, they are the grid, U, V, and collection (anode) plane. The construction material of the TPC is FR4 glass fiber composite. All wire planes have 75 $\mu$m diameter copper beryllium wire spaced 3 mm apart, and the plane separation is 3.125 mm. Each wire plane has 667 wires. The U and V planes detect the induced signal when the electron passes through the wires. The U and V wires are oriented $\pm 60$ degrees with respect to the anode wires. The anode wires measure the coordinate in direction of the track and U and V are orthogonal to the track. The third coordinate is determined by the drift time to the anode plane.

The field cage is realized in two modules: the drift cage module, and the wire plane module. The wire plane module incorporates a 2.54 cm thick FR4 structural component that supports the load of the four wire planes so that the wire tension is maintained. The field cage is double sided gold plated copper clad FR4 arranged with 5 mm wide traces separated by 1 cm. A resistive divider chain provides the voltage for each trace. The design voltage gradient on the divider chain is 500 V/cm when 50 kV is applied to the cathode. The electrons from the ionized event are collected on the anode plane. The U and V planes detect signals via induction, and are made transparent to electrons via biasing. The drift velocity of the electrons with 500 V/cm is 1.6 mm/$\mu$s.

## 4.5 Photon Detection System

Simulations show that detection of several photoelectrons per MeV for a minimum ionizing particle (MIP) in a TPC with a field of 500 V/cm improves the projected energy resolution of the detector by 10-20%. Such improvement stems from the anti-correlation between the production of scintillation photons and ionization electrons, a phenomenon which has been conclusively observed to improve calorimetry already in liquid xenon [42]. Hints of it have already been seen in reanalysis of older liquid argon data that included simultaneous measurements of light and charge yields at the same electric fields [43]. If confirmed by CAPTAIN, it will increase the utility of the photon detection systems of other experiments such as DUNE, as well as argon-based dark matter detectors.

Liquid argon scintillates at a wavelength of 128 nm which unfortunately is readily absorbed by most photodetector window materials. It is thus necessary to shift the

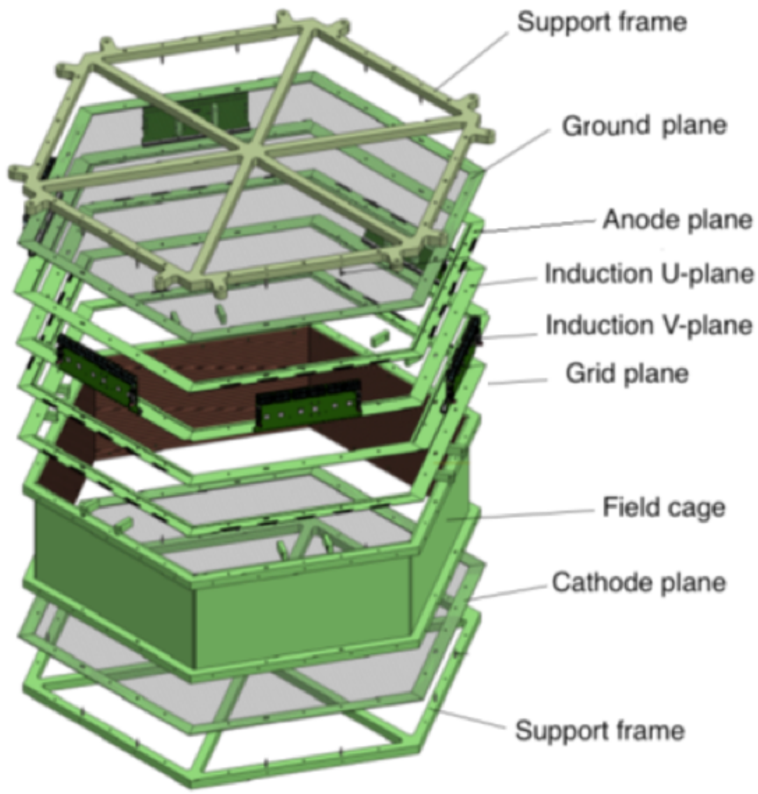



Figure 9: Diagram of CAPTAIN TPC

light to the visible. The photon detection system is composed of a wavelength shifter covering a large area of the detector and a number of photodetectors to collect the visible light. The baseline CAPTAIN photon detection system uses tetraphenyl butadiene (TPB) as a wavelength shifter and sixteen Hamamatsu R8520-500 photomultiplier tubes (PMT) for light detection. The R8520 is a compact PMT approximately 1" x 1" x 1" in size with a borosilicate glass window and a special bialkali photocathode capable of operation at liquid argon temperatures (87 K). It has a 25% quantum efficiency at 340 nm and is the most commonly used wavelength shifter for liquid argon detectors. It has a re-emission spectrum that peaks at about 420 nm [44]. The TPB will be coated on a thin piece of acrylic in front of the PMTs. Eight PMTs will be located on top of the TPC volume and eight on the bottom. This will provide a minimum detection of 2.2 photoelectrons per MeV for a MIP. The amount detected will increase if the entire top and bottom surfaces are coated with TPB.

The PMTs will use a base with cryogenically compatible discrete components. The cable from the base to the cryostat feedthrough is Gore CXN 3598 with a 0.045" diameter to reduce the overall heat load. The PMT signals will be digitized at 250 MHz using two 8- channel CAEN V1720 boards. The digitizers are read out through fiber optic cables by a data acquisition system written for the MiniCLEAN experiment [45].

## 4.6 Laser Calibration System

The first measurement of photoionization of liquid argon was performed by Sun et al. [46]. Using frequency quadrupled Nd-YAG laser to generate 266-nm light the authors demonstrated that the ionization was proportional to the square of the laser intensity. The ionization potential of liquid argon is 13.78 eV, slightly lower than the energy of three photons from a 266-nm quadrupled Nd-YAG laser. The ability to create well-defined ionization tracks within a liquid argon TPC provides an excellent calibration source that can be used to measure the electron lifetime in-situ and to determine the drift field within the TPC itself. Significant progress has been made in this field and is documented in Rossi et al. [47]. The CAPTAIN TPC provides an excellent test bed for a future DUNE laser calibration system.

To avoid surface irregularities that may disperse the laser beam the CAPTAIN TPC will employ optical access on the sides of the detector. A LANL existing Quantel Brilliant B Nd-YAG laser will be used to ionize the liquid argon. The design seeks to be flexible and allow several paths through the liquid argon, including parallel and at an angle to the wire plane. This will allow us to determine the electron lifetime within the CAPTAIN TPC.

## 4.7 Current Status

At the present time, the mini-CAPTAIN detector is being commissioned at LANL. Mini-CAPTAIN has been successfully filled with liquid argon and cooled, and the electronics, DAQ, purification system, and laser calibration system are all being tested. In Summer 2015, mini-CAPTAIN will take cosmic-ray data, and we expect to run mini-CAPTAIN in a neutron beam at the Los Alamos Neutron Science Center (LANSCE) for approximately one week during the next beam cycle (October 2015 - January 2016). The CAPTAIN electronics, field cage, and cryostat are all in hand, and the wiring of the TPC is planned to be conducted at UC Irvine. The CAPTAIN purification system is with the vendor, and is expected to be delivered in Fall 2015.

# 5 Installation and Operation Issues

## 5.1 Relative Sizes of Detectors

The CAPTAIN detector is of a comparable fiducial mass to that of the inner tracking region of the MINER$\nu$A detector, so the statistical uncertainties for both samples are comparable. Figure 10 shows one potential location for the CAPTAIN detector: in this case the nuclear target region of the MINER$\nu$A detector has been removed but most of the scintillator target is still in place. Figure 11 shows the relative sizes of the CAPTAIN and MINER$\nu$A detectors as seen by the neutrino beam. It is clear from these two diagrams that the CAPTAIN detector would fit conveniently in front of the MINER$\nu$A detector and could be supported from below to be centered on the neutrino beam.

The ultimate location of the CAPTAIN detector depends on whether or not the nuclear target region of the MINER$\nu$A detector is unstacked but most of the technical challenges associated with installing and operating the CAPTAIN detector underground are independent of the details of that location.

The MINOS shaft through which all equipment must pass to be installed underground is roughly half of a cylinder that is 22 feet in diameter as shown in Figure 12. The 15-ton capacity crane that operates in the shaft is adequate to lower the vessel, which when empty weighs 5 tons. A cart will need to be built to accept the vessel when it reaches the lower level, and the cart can be pulled using the same fork-truck by which the MINOS and MINER$\nu$A detectors were installed.

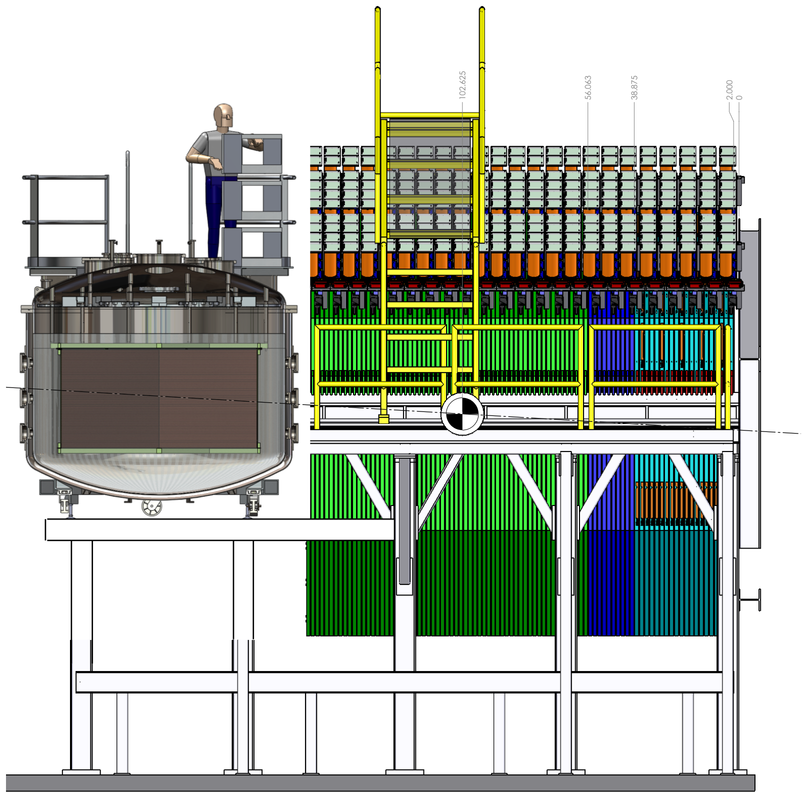



Figure 10: Relative size and possible location of the CAPTAIN detector in front of the MINER$\nu$A detector. The neutrino beam travels from left to right at an angle of 58 mrad to the horizontal.

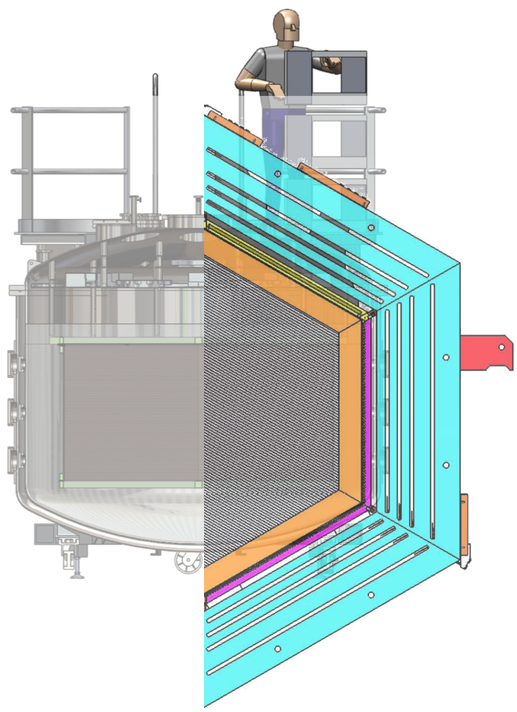


Figure 11: Relative transverse sizes of the CAPTAIN and MINER$\nu$A detectors, as seen from the incoming neutrino beam.

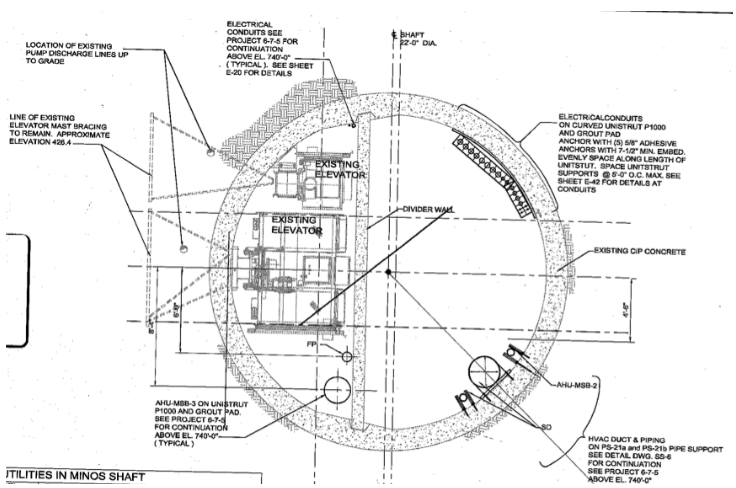



Figure 12: Drawing of the MINOS shaft, dimensions are in feet.

## 5.2 Remote Operations

The CAPTAIN detector will need to be operable remotely since staffing two people on shift underground 24 hours a day is prohibitive due to the small size of the joint CAPTAIN-MINER$\nu$A collaboration. During the Los Alamos running the CAPTAIN detector's cryogenic control system can not be operated remotely, so that upgrade will be an important cost of running CAPTAIN in the NuMI beamline. A smaller version of the MicroBooNE cryogenic control system would be appropriate for this (given the smaller volume of liquid argon that is supported).

## 5.3 Safety Issues

The largest safety issue associated with CAPTAIN-MINER$\nu$A is the fact that this volume of liquid argon represents a significant oxygen deficiency hazard (ODH) if for some reason the vessel were to leak catastrophically. Because of the relative density of argon to oxygen, the oxygen in the underground cavern would relatively quickly be displaced.

The solutions to mitigate this hazard are already being examined in the context of the DUNE liquid argon operations and involve careful containment and then venting of any potentially spilled argon. There is currently a 19-inch diameter shaft in the downstream end of the MINOS ND hall; that shaft could be part of the venting system in addition to the upstream shaft. Nevertheless it is likely that people working underground would need to bring supplies of oxygen with them, and the area would no longer be classified as an ODH class 0 enclosure. These restrictions are not unprecedented either at this laboratory or at other laboratories worldwide, and are not seen as prohibitive.

# 6 Resource Requirements

The technical resource requirements for the infrastructure needed to install CAPTAIN underground, fill it with argon, and maintain the argon in its liquid state depend on the cooling method chosen. The labor and M&S estimates here assume that CAPTAIN will be cooled by cryocoolers underground, rather than by running a heat exchanger with a liquid nitrogen supply, as was assumed for the letter of intent and as is done in MicroBooNE. Using a cryocooler underground will reduce the labor costs associated with installing pipes that run the length of the shaft, and also will reduce the ODH risks because the total volume of cryogens underground will be much smaller. The heat load for CAPTAIN is calculated to be 700 W, and so CAPTAIN could be easily serviced by two 600-W units. For reference, the mini-CAPTAIN measured heat load is 230 W, which is very close to the expected rate.

The remainder of this section provides estimates for the labor and materials that would be needed to mount this program, assuming that CAPTAIN would run in the location just upstream of the MINER$\nu$A solid nuclear target region. This means that MINER$\nu$A's cryogenic helium target would have to be dismantled and removed to make room for CAPTAIN, but everything else would stay as it is currently configured in the hall. This configuration would allow for the largest installation flexibility: if CAPTAIN were ready to be installed before MINER$\nu$A received its full $12 \times 10^{20}$ POT in antineutrino mode, then the installation could proceed and MINER$\nu$A could continue to meet its original core physics mission, which is to measure cross section ratios on nuclear targets in both neutrino and antineutrino beams. If the upstream portion of the MINER$\nu$A detector were to be removed, then the mechanical technician needs would be higher and are not included here. Many of these estimates are based on extrapolations from the as-realized labor needs for the MicroBooNE installation and commissioning.

## 6.1 Cryogenic Engineering

Figure 13 shows the current design for the handling of the liquid argon for the CAPTAIN detector while it is underground in the NuMI beamline. The pump suction comes off the bottom of the tank. One of the top side ports is used to return the liquid argon. Work done at Fermilab on other liquid argon vessels indicates that most of the contamination is in the warmer gas. Therefore, the current design returns the liquid to the vessel using a phase separator which keeps the liquid from passing through the warm gas and thus being contaminated again. One alternative to an Ar/H2 mixture is to use industrial pure argon, similar to how MicroBooNE operates, with a 500 liter dewar.

## 6.2 Engineer Labor Estimate

Table 2 provides a list of the engineering tasks needed in order to design the system necessary to install and operate the CAPTAIN detector underground, not including controls engineering or preparations for Operational Readiness Clearance reviews which are provided in later sections. The estimated duration of each task is also provided. Including 40% contingency, the total number of engineer days required is 184.

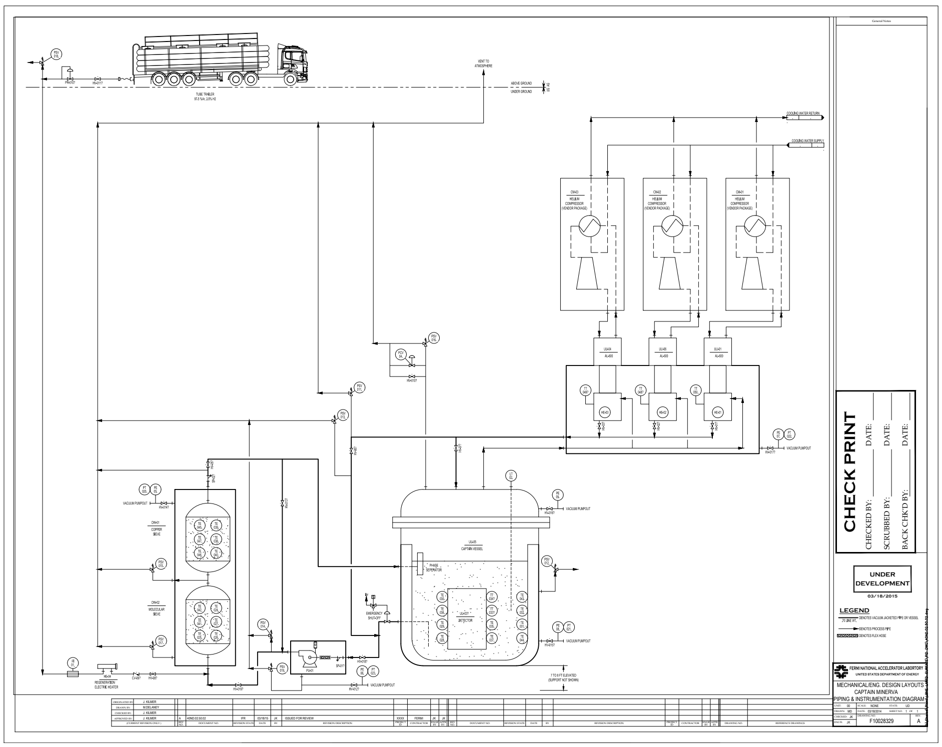



Figure 13: Flow diagram for the CAPTAIN detector in the underground enclosure.

| Task | Duration (Days) |
|---|---|
| Develop Piping and Instrumentation Diagram | 5 |
| Design vent stack | 10 |
| Complete Oxygen Deficiency Hazard calculations | 30 |
| Design heat exchangers for 600 W refrigerators | 5 |
| Design manifold box for refrigerators | 15 |
| Size piping | 3 |
| Layout equipment in cavern | 3 |
| Pressure vessel notes for CAPTAIN | 20 |
| Produce Engineering note for CAPTAIN support frame | 5 |
| Produce Engineering note for TPC installation frame | 5 |
| Assemble Instrument and valve list | 3 |
| Develop Operating procedures | 3 |
| Produce Piping engineering notes | 20 |
| Size relief valves | 5 |
| Total | 132 |
| Add 40% Contingency | 184 |

Table 2: List of tasks requiring engineering in order to install and operate the CAPTAIN detector underground in front of the MINER$\nu$A detector.

### 6.3 Drafting Labor Estimate

Table 3 provides a list of the drafting tasks needed to complete the design of the systems to install and operate the CAPTAIN detector underground, not including drafting requirements for the controls system which is provided in a later section.

| Task | Duration (Days) |
|---|---|
| Draw Piping and Instrumentation Diagram | 10 |
| Draw Vent line | 20 |
| Draw support frame | 5 |
| Draw TPC installation frame | 5 |
| Draw layout of equipment in cavern | 20 |
| Draw up refrigerator box | 20 |
| Solid model of piping and physical arrangement | 60 |
| Piping fabrication drawings | 60 |
| Total | 200 |
| Add 40% contingency | 280 |

Table 3: List of tasks and associated drafter days needed in order to install and operate the CAPTAIN detector underground in front of the MINER$\nu$A detector.

### 6.4 Mechanical Technician Labor Estimate

Table 4 provides a list of tasks that are associated with removing the upstream helium target from the MINER$\nu$A detector configuration, installing the CAPTAIN detector and associated infrastructure underground, along with estimates for the mechanical technician labor that is required for those tasks, using actual levels of effort needed for similar MicroBooNE activities or MINER$\nu$A helium target activities. This does not include labor required for controls or Operational Readiness Review processes. The total number of technician days required for this part of the experiment, including 40% contingency, is 686.

### 6.5 Welding Estimate

Table 5 provides a description of the welding needed to complete the design of the systems to install and operate the CAPTAIN detector underground.

| Task | Duration (Days) | Technicians Needed | Technician Days |
|---|---|---|---|
| Clean cavern prior to start | 1 | 4 | 4 |
| Install new 6" vent pipe | 20 | 3 | 60 |
| Remove roof, section supports, camera, alarms, VESDA | 1 | 4 | 4 |
| Remove Veto Walls | 4 | 4 | 16 |
| Empty Helium target | 10 | 4 | 40 |
| Remove helium target vacuum pumps, water cooling, refrigerator | 2 | 4 | 8 |
| remove target piping top platform | 2 | 4 | 8 |
| Remove helium target stand and target | 3 | 4 | 12 |
| Prefab support frame for captain | 10 | 2 | 20 |
| Assemble support frame in cavern | 2 | 4 | 8 |
| Bring down CAPTAIN | 1 | 4 | 4 |
| Position and assemble new cryo system | 120 | 2 | 240 |
| Prefabrication and installation of TPC maintenance frame | 15 | 2 | 30 |
| Install detectors in captain | 3 | 4 | 12 |
| Reposition vessel on stand | 1 | 4 | 4 |
| Re-install Veto walls | 4 | 5 | 20 |
| Total Mechanical Technician work | | | 490 |
| Add 40% contingency | | | 686 |

Table 4: List of tasks requiring mechanical technician labor, as estimated using actual duration for similar MicroBooNE activities.

| Task | Duration (Days) |
|---|---|
| Weld support frame | 10 |
| Weld TPC frame | 10 |
| Weld vent line | 20 |
| Weld cryogenic piping | 40 |
| Total welding | 80 |

Table 5: List of tasks requiring a welder, and estimated duration for each task.

## 6.6 Controls Labor Estimate

The controls labor estimate is based on the MicroBooNE controls system tasks and is described in Table 6. The numbers listed do not include contingency.

| Controls Labor Needed | Person-days |
|---|---|
| Electrical Engineer | 54 |
| Electrical Technician | 79 |
| PC Administrator | 13 |
| Drafter | 15.5 |
| Calibration | 9 |
| Electrician | 9 |

Table 6: Summary of labor resource needs for CAPTAIN controls. Contingency is not included.

## 6.7 Electrical Safety Review Labor Estimate

There are four recommended steps associated with passing the electrical safety reviews that are required for every operating experiment at Fermilab. First, all custom designed chassis go through a Safety Engineering Design Review (SEDR) at the prototype stage of the design. After that, all components must be installed in what is called a "production" rack which is then reviewed for a partial operational readiness clearance (pORC) at a test location. Then the racks are moved to the final experiment location, and a new pORC review is done, but because of the earlier steps it is more straightforward. The fourth step is the Final ORC walk-through. It is estimated that an Electrical Engineer or Engineering Physicist with the right expertise would be needed for roughly one month for the first step, then one to two weeks for setting up the pORC at the experimental area, then two days for the final walk-through. An Electrical Technician will be needed for roughly three days per rack, with an estimate of four racks. A Mechanical Technician will be needed for approximately one day per rack, again with an estimate of four racks. In addition, the time for an electrical review committee will be needed, but with the multi-step approach outlined here this time can be minimized, especially if the committee is the same for all review steps. Table 7 summarizes the labor needs for all steps.

| Step | Electrical Engineer | Electrical Technician | Mechanical Technician |
|---|---|---|---|
| SEDR | 10 days | 12 days | 4 days |
| pORC at test location | 12 days | 12 days | 4 days |
| pORC at Experiment | 5 days | 12 days | 4 days |
| Final ORC walk-through | 2 days | - | - |
| Total | 29 days | 36 days | 12 days |

Table 7: Summary of labor resource needs for the electrical safety review. Contingency is not included.

## 6.8 Technically Driven Schedule

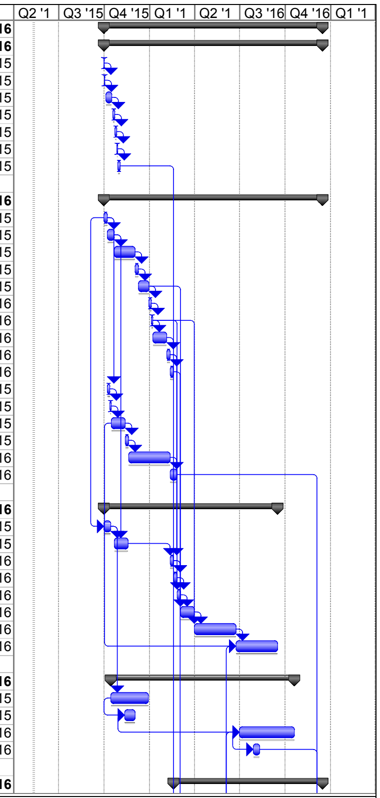
Given the tasks outlined above a rough plan has been constructed to understand what a technically driven schedule might be. That plan is shown in Figures 14 and 15. The work to prepare the cavern for installation will take roughly two and a half months and would best be done during an accelerator shutdown. Some of the engineering can be done in parallel if enough engineers are available, and it is possible that more work than is currently shown could go on in parallel. This exercise shows that from the start of the piping and instrumentation diagram (P&ID) development through the experiment being ready for operations, a minimum of 15 months are needed.

If the CAPTAIN detector arrives on site as early as Fall 2016, that would imply that the engineering would need start in Summer 2015 in order for the infrastructure underground to be ready. In other words, in order to maintain the maximum level of flexibility of this program with other CAPTAIN programs, the engineering should start as early as engineering resources can be allocated.

There are several other schedule constraints that are not shown in Figures 14 and 15. To maximize the data collected by the MINER$\nu$A detector, it would be best to install the CAPTAIN detector underground during a long (several week) accelerator maintenance shutdown.

In order for the work to go at this schedule the project would need to have more than one engineer working for roughly the first quarter of this project, as shown in Table 8. This gives the number of person-weeks per quarter for the work described above.

| ID | Task Name | Duration | Start | Finish |
|---|---|---|---|---|
| 1 | **Project Start** | **316 days?** | **Thu 10/1/15** | **Thu 12/15/16** |
| 2 | **Preparation Work** | **316 days?** | **Thu 10/1/15** | **Thu 12/15/16** |
| 3 | Clean Cavern Prior to Start | 1 day | Thu 10/1/15 | Thu 10/1/15 |
| 4 | Remove Roof, supports, Cameras, alarms, VESDA | 1 day | Fri 10/2/15 | Fri 10/2/15 |
| 5 | Empty helium target and warm up | 10 days | Mon 10/5/15 | Fri 10/16/15 |
| 6 | Remove Veto walls | 4 days | Mon 10/19/15 | Thu 10/22/15 |
| 7 | Remove HE target vacuum pumps, water cooling, compressor | 2 days | Fri 10/23/15 | Mon 10/26/15 |
| 8 | Remove target vent piping and top platform | 2 days | Tue 10/27/15 | Wed 10/28/15 |
| 9 | Remove helium target and stand | 3 days | Thu 10/29/15 | Mon 11/2/15 |
| 10 | | | | |
| 11 | **Engineeering Design** | **316 days?** | **Thu 10/1/15** | **Thu 12/15/16** |
| 12 | Develop P&ID | 5 days | Thu 10/1/15 | Wed 10/7/15 |
| 13 | Design vent stack | 10 days | Thu 10/8/15 | Wed 10/21/15 |
| 14 | ODH calculations | 30 days | Thu 10/22/15 | Wed 12/2/15 |
| 15 | Design Heat exchangers for 600 Watt refrigerators | 5 days | Thu 12/3/15 | Wed 12/9/15 |
| 16 | Design Manifold box for refrigerators | 15 days | Thu 12/10/15 | Wed 12/30/15 |
| 17 | Size piping | 3 days | Thu 12/31/15 | Mon 1/4/16 |
| 18 | Layout Equipment in Cavern | 3 days | Tue 1/5/16 | Thu 1/7/16 |
| 19 | Pressure vessel note for Captain Vessel | 20 days | Fri 1/8/16 | Thu 2/4/16 |
| 20 | Engineering note for Captain Support frame | 5 days | Fri 2/5/16 | Thu 2/11/16 |
| 21 | Engineering note for TPC installation frame | 5 days | Fri 2/12/16 | Thu 2/18/16 |
| 22 | Instrument and Valve summary | 3 days | Thu 10/8/15 | Mon 10/12/15 |
| 23 | Operating Procedures | 3 days | Tue 10/13/15 | Thu 10/15/15 |
| 24 | Piping Engineering notes | 20 days | Fri 10/16/15 | Thu 11/12/15 |
| 25 | Size relief valves | 5 days | Fri 11/13/15 | Thu 11/19/15 |
| 26 | Get approval for safety documents from CSS | 60 days | Fri 11/20/15 | Thu 2/11/16 |
| 27 | ORC for cryo operations | 10 days? | Fri 2/12/16 | Thu 2/25/16 |
| 28 | | | | |
| 29 | **Drafting effort** | **251 days** | **Thu 10/1/15** | **Thu 9/15/16** |
| 30 | Draw P&ID | 10 days | Thu 10/1/15 | Wed 10/14/15 |
| 31 | Draw Vent line | 20 days | Thu 10/22/15 | Wed 11/18/15 |
| 32 | Draw Support Frame | 5 days | Fri 2/12/16 | Thu 2/18/16 |
| 33 | Draw TPC Installation Frame | 5 days | Fri 2/19/16 | Thu 2/25/16 |
| 34 | Draw Layout of equipment in Cavern | 5 days | Fri 2/26/16 | Thu 3/3/16 |
| 35 | Draw up Refrigerator Manifold box | 20 days | Fri 3/4/16 | Thu 3/31/16 |
| 36 | Solid model of piping and physical arangement | 60 days | Fri 4/1/16 | Thu 6/23/16 |
| 37 | Piping fabrication Drawings | 60 days | Fri 6/24/16 | Thu 9/15/16 |
| 38 | | | | |
| 39 | **Controls** | **265 days** | **Thu 10/15/15** | **Wed 10/19/16** |
| 40 | Engineer system and safety documents | 54 days | Thu 10/15/15 | Tue 12/29/15 |
| 41 | Draft controls system | 15 days | Thu 11/12/15 | Wed 12/2/15 |
| 42 | Fabricate controls | 79 days | Fri 7/1/16 | Wed 10/19/16 |
| 43 | Electrician effort | 9 days | Fri 7/29/16 | Wed 8/10/16 |
| 44 | | | | |
| 45 | **Fabrication and Installation** | **215 days?** | **Fri 2/19/16** | **Thu 12/15/16** |

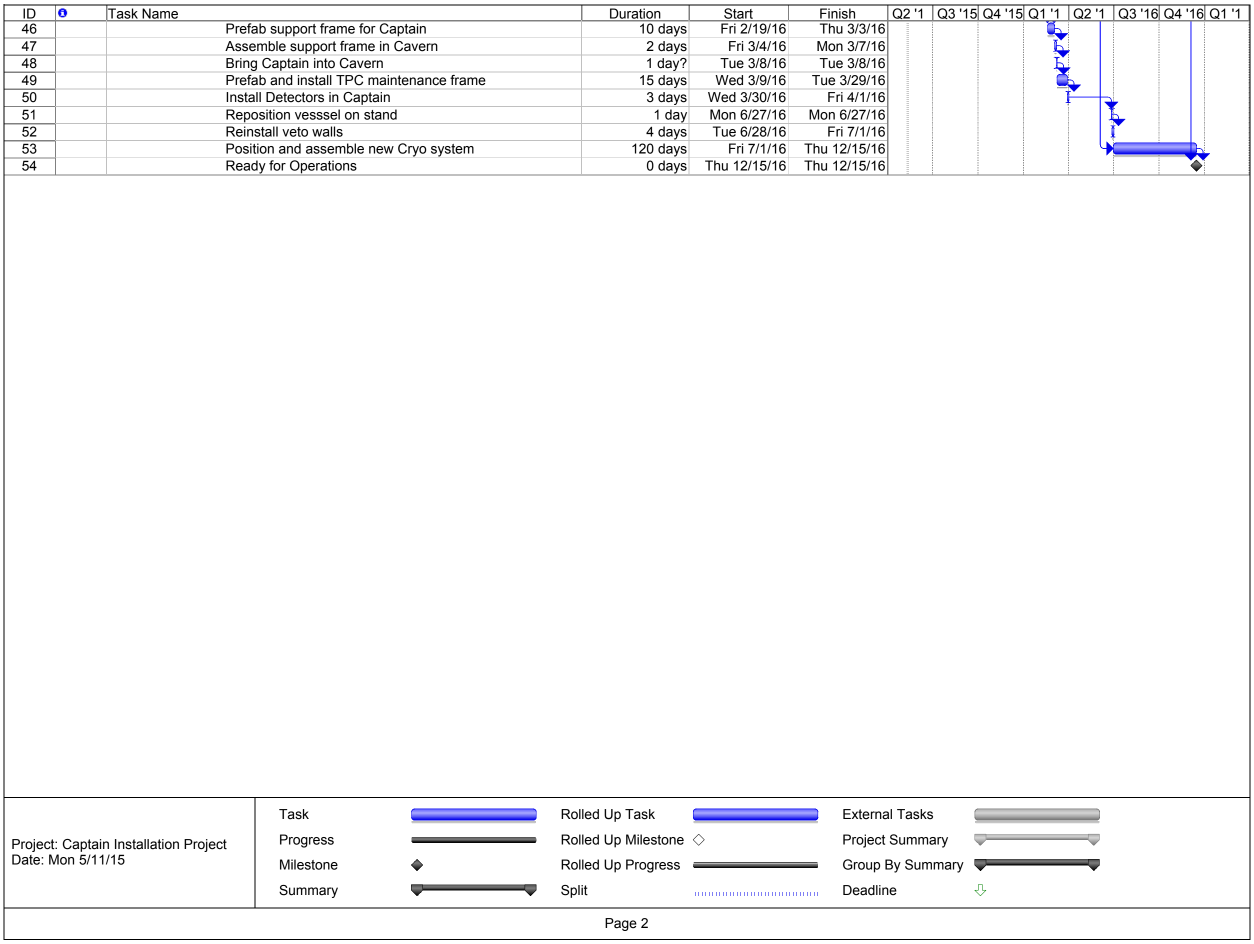



Project: Captain Installation Project
Date: Mon 5/11/15

| | | |
|---|---|---|
| Task | Rolled Up Task | External Tasks |
| Progress | Rolled Up Milestone | Project Summary |
| Milestone | Rolled Up Progress | Group By Summary |
| Summary | Split | Deadline |

Page 1

Figure 14: Technically driven schedule for the CAPTAIN detector to be built and installed underground, part 1.




| ID | Task Name | Duration | Start | Finish |
|---|---|---|---|---|
| 46 | Prefab support frame for Captain | 10 days | Fri 2/19/16 | Thu 3/3/16 |
| 47 | Assemble support frame in Cavern | 2 days | Fri 3/4/16 | Mon 3/7/16 |
| 48 | Bring Captain into Cavern | 1 day? | Tue 3/8/16 | Tue 3/8/16 |
| 49 | Prefab and install TPC maintenance frame | 15 days | Wed 3/9/16 | Tue 3/29/16 |
| 50 | Install Detectors in Captain | 3 days | Wed 3/30/16 | Fri 4/1/16 |
| 51 | Reposition vesssel on stand | 1 day | Mon 6/27/16 | Mon 6/27/16 |
| 52 | Reinstall veto walls | 4 days | Tue 6/28/16 | Fri 7/1/16 |
| 53 | Position and assemble new Cryo system | 120 days | Fri 7/1/16 | Thu 12/15/16 |
| 54 | Ready for Operations | 0 days | Thu 12/15/16 | Thu 12/15/16 |

Figure 15: Technically driven schedule for the CAPTAIN detector to be built and installed underground, part 2.

| Resource | Quarter 1 | Quarter 2 | Quarter 3 | Quarter 4 | Quarter 5 |
|---|---|---|---|---|---|
| Mechanical Technician | 20 | 16 | 5 | 30 | 24 |
| Electrical Technician | 0 | 0 | 0 | 15 | 3 |
| Mechanical Engineer | 22 | 11 | 0 | 0 | 0 |
| Controls Engineer | 12 | 0 | 0 | 0 | 0 |
| Mechanical Drafter | 7 | 8 | 14 | 12 | 0 |
| Electrical Drafter | 3 | 0 | 0 | 0 | 0 |

Table 8: Resources needed by quarter, in units of person-weeks.

# 7 Cost Estimate

Apart from the cost of the labor required for this proposal, the remainder of the costs are dominated by the cost of hardware and the cost of the refrigeration. The estimates for the labor given above and the materials estimates here are made assuming that Los Alamos National Laboratory will supply a filter vessel and pump for liquid flow for the system. The CAPTAIN vessel itself is already ASME code stamped.

Refrigeration can be provided by the use of two 600 W cryorefrigerators. These units can be water cooled. The stainless compressor lines need to be 60 feet long. The cold head motor cord also must be 60 feet long. This specification was met with the AL600 cryorefrigerator which is produced by the Cryomech company. At the time of this proposal the cost for three units (two plus a spare so that we do not lose argon in the case of a cryorefrigerator failure) is $183.7k. A quote for these units as well as engineering drawings and a capacity curve can be found in Appendix A.

The cost estimate for the cryogenic control system hardware is based on MicroBooNE. Details can be found in Appendix B.

The CAPTAIN vessel holds about 7000 liters. Including the boil off and some waste in filling, the experiment would need an argon dewar of 10000 liters (2600 gallons). The current cost that Fermilab is paying for liquid argon is $4.50/100 standard cubic feet. This means that to fill CAPTAIN one time would cost $9k. We conservatively assume that two complete fills will be made initially, one for commissioning and one for operations. The cryostat will use an indium seal. The seals cost $6k each, and we assume that we will need two seals (one for each complete fill). With the current CAPTAIN cryogenic systems the argon loss rate is roughly 1% per day, which would translate to an estimated operations cost of roughly $35k per year. However the current design for underground operations would not involve the loss of any argon, and so the argon might only need to be replaced when the cryocoolers are refurbished.

There are costs associated with hardware for the cryostat. For example, gaskets are required every time any flange is opened. Additional hardware could be required should we decide to make any changes to the instrumentation after further evaluation. This might include additional valves, replacement flex hoses, bolts, etc. We estimate the cost of cryostat hardware to be approximately \$45k.

A temporary clean room will be required when the TPC is inserted in the cryostat. The clean room requirements are not strict; an area separated with plastic sheeting and basic air filtering will likely be sufficient. Personal protective equipment (PPE) and clean room gear such as Tyvek suits and gloves will be required by those assembling CAPTAIN at Fermilab.

Additional materials costs include \$10k for cabling and \$50k for custom vacuum insulated piping and relief valves. The estimated cost to ship CAPTAIN to Fermilab is approximately \$25k.

The materials costs are summarized in Table 9. Other costs not included here are the costs of the DAQ computers (purchasing new computers or shipping existing ones from Los Alamos) and consumables needed for the CAPTAIN stand. It is expected that much of the steel for the CAPTAIN stand could be repurposed from the current helium target stand that is in front of MINER$\nu$A at the time of this writing. Similarly, the fixturing for underground installation would likely be made from steel that is available on site.

The labor needed for the project has been described above, and the total labor cost associated with this proposal will depend greatly on the specific individuals who are available. Bringing in outside contract labor is an option that might relieve some of the schedule delay associated with having people work part time on the project. The labor needs are summarized in Tables 6 and 10.

# 8 Computing

## 8.1 Offline

CAPTAIN uses a software framework based on the T2K ND280 software. The framework is based on the ROOT analysis framework [48] and is designed to be modular with as few outside dependencies as possible. MINER$\nu$A uses the Gaudi software framework [49], which is used by several particle physics experiments, but not supported by Fermilab. Because CAPTAIN and MINER$\nu$A are operating under independent software frameworks, joint reconstruction will be performed using sepa-

| Item | Cost (FY15 k$) |
| --- | --- |
| Cryocoolers | 184 |
| Liquid argon | 18 |
| Controls hardware | 27 |
| Indium seals | 12 |
| Cryostat hardware | 45 |
| Temporary clean room | 13 |
| PPE/Clean room gear | 7 |
| Cabling | 10 |
| Vacuum insulated piping and valves | 50 |
| Shipping | 25 |
| Total Base | 391 |
| Contingency | 120 |
| Total | 511 |

Table 9: Summary of materials costs for CAPTAIN-MINER$\nu$A. All costs are in FY15 dollars. We assume 20% contingency on the quoted price for the cryocoolers and 40% contingency on all other items.

| Labor Resource | Person-Days |
| --- | --- |
| Technician | 530 |
| Engineer | 192 |
| Drafter | 220 |
| Welder | 80 |

Table 10: Summary of labor needs for CAPTAIN-MINER$\nu$A installation and commissioning, not including controls. Contingency is not included.

rately reconstructed objects from each detector. This is similar to the situation with MINER$\nu$A and the MINOS ND, where the MINER$\nu$A and MINOS track matching is done with tracks that have been reconstructed independently in each detector. T2K also operates in this manner, where inputs are combined from completely independent parts of the experiment (beamline, ND280, SK) as well as dedicated external inputs (e.g., SHINE).

A fully joint reconstruction within the same software framework is not a prerequisite for CAPTAIN-MINER$\nu$A physics analyses. However, CAPTAIN-MINER$\nu$A could serve as a model for a DUNE near detector system, and therefore, there is a benefit to demonstrating a fully integrated reconstruction. DUNE will use LArSoft [50], a software package for simulation, reconstruction, and analysis that was designed to work for all planned and running liquid argon experiments at Fermilab. LArSoft is built on the art analysis framework supported by the Fermilab Scientific Computing Division. A long-term goal of the CAPTAIN-MINER$\nu$A program is to demonstrate a joint reconstruction within an art-based framework that includes LArSoft for CAPTAIN. This would require a migration to a new framework for both CAPTAIN and MINER$\nu$A.

Regardless of an eventual migration to LArSoft, the results from the CAPTAIN-MINER$\nu$A program are intended to benefit DUNE or other liquid argon experiments, and therefore, any algorithms that are developed for event reconstruction in CAPTAIN will be made available for use in other experiments and software frameworks. CAPTAIN will also seek to implement algorithms developed by other liquid argon experiments, such as MicroBooNE, into the CAPTAIN reconstruction.

## 8.2 Online

CAPTAIN's DAQ software is based on artdaq and is similar, though not identical, to the DAQ software used by MicroBooNE. artdaq is a data acquisition toolkit for particle physics experiments that is supported by the Fermilab Scientific Computing Division and can be integrated with the art software framework.

MINER$\nu$A's DAQ software and electronics is discussed in [51]. Central to the software is a JLAB program called ET (Event Transfer), a core package of the CODA suite [52]. MINER$\nu$A uses ET for many of the same functions that artdaq provides, and for the detector monitoring inter-process communication suite.

## 8.3 Data Storage and Processing

### 8.3.1 CAPTAIN

The computing needs for the CAPTAIN TPC in the CAPTAIN-MINER$\nu$A experiment have been evaluated based on an expected 180 days of beam per year, assuming a beam spill every 1.3 s. (One year is equivalent to approximately $6 \times 10^{20}$ POT.) As one of the goals of this experiment is to collect a library of event topologies, the data is assumed to be collected using a minimum bias beam trigger with the full TPC and photosensor data for each beam spill being recorded without zero suppression. We have also included the estimated resources needed to calibrate the detector as well as produce a sample of simulated neutrino interactions for the CAPTAIN-MINER$\nu$A exposure to the NuMI beam.

Table 11: The estimated data size for the CAPTAIN TPC and photon detection system. The first column shows the estimated size collected during a one-year beam exposure. The second column shows the size of the associated simulation. The third column shows the total for both the beam exposure and simulation.

| | CAPTAIN | Simulation | Total |
|---|---|---|---|
| Beam triggers per year | $1.2 \times 10^7$ | $3.6 \times 10^7$ | $4.8 \times 10^7$ |
| Size per beam trigger | 8.4 MB | 14.2 MB | 22.6 MB |
| Size per year | 272 TB | 512 TB | 784 TB |

The data size has been estimated based on the assumption that a copy of the CAPTAIN raw data, the data after calibration, and a summary of the reconstruction results for use in physics analysis will be retained. The results are summarized in Table 11. For the simulation, only a copy of the "calibrated" simulation and a summary of the reconstruction results will be retained. The data size per spill has been estimated based on a TPC integration window of 1875 $\mu$s and a sample time of 500 ns. The CAPTAIN photon detection system is assumed to have an integration window of 1800 $\mu$s and a sample time of 5 ns. Based on experience with the prototype detector, we are assuming a 70% compression factor. The size of calibration data has not been explicitly estimated, but has been accounted for based on the assumption that 10% of our triggers will be from the calibration system.

Management of the data will require databases for both the calibration constants and detector status measurements (i.e. slow control). Neither data base is expected to be large. Because the TPC and photon detection system are inside a pressure controlled cryogenic vessel, the response is assumed to be quite stable. For this reason, we have assumed that the calibration constants will only be updated four times per day, and the calibration data base is expected to grow at a rate of 180 MB per year. The slow control database is expected to grow at a rate of 5 GB per year.

Table 12: The estimated processing requirements for the CAPTAIN TPC, and photon detection system. The first column shows the estimated requirement for the beam exposure. The second column shows the requirement for the associated simulation. The third column shows the total processing requirement.

| | CAPTAIN | Simulation | Total |
|---|---|---|---|
| Processing per trigger | 3.4 s | 3.75 s | N/A |
| Processing per year | 472 cpu-days | 1563 cpu-days | 2035 cpu-days |
| Reprocessing per year | 3 | 3 | N/A |
| Total processing per year | 1415 cpu-days | 4689 cpu-days | 6104 cpu-days |

The computing resources required to analyze the CAPTAIN data have been estimated based on the current event reconstruction, allowing for 200% increase in the processing time per event as the event reconstruction grows in sophistication. Using an Intel Xeon E5405 at 2 GHz as the benchmark processor, we expect a processing time of 3.4 s per event for CAPTAIN and 3.75 s per event for the simulation. The results are summarized in Table 12. This leads to a total processing time of 2035 cpu-days for each time that CAPTAIN and simulation data are reconstructed. Assuming that we will repeat the reconstruction three times per year, this leads to a total processing usage of 6104 cpu-days per year.

### 8.3.2 MINER$\nu$A

For FY2016, MINER$\nu$A estimates a total processing usage of approximately $1.2 \times 10^6$ cpu-days and data storage usage of approximately 2 PB. We expect MINER$\nu$A will have similar storage and processing requirements per year in the CAPTAIN-MINER$\nu$A era.

## 8.4 Computing Requirements

- Framework support. MINER$\nu$A currently uses the Gaudi software framework for offline processing and analysis, while CAPTAIN uses their own ROOT-based framework. Long-term support for Gaudi is problematic for MINER$\nu$A-the framework is sound but migrating dependencies with operating system evolutions and taking full advantage of the development resources at Fermilab is challenging. Furthermore, supporting two different frameworks for analysis can be difficult, although the MINER$\nu$A experience working with MINOS ND data shows that it is possible.

Nevertheless, migrating the existing MINER$\nu$A software framework into art could potentially be very valuable. It would make long-term support for the MINER$\nu$A code much simpler and would make it more straightforward to take advantage of developments at Fermilab that are targeted at art. It would additionally make it simpler for analyzers in CAPTAIN and MINER$\nu$A to share code and for developers to contribute to both code bases. Finally, it would also simplify offline production and simulation if all the steps required to analyze CAPTAIN-MINER$\nu$A data if all the details of both could be captured (when appropriate) in single programs.

This migration would be a very significant project though and would require an individual at the physics applications developer level at least six months of full-time effort, in addition to some effort from MINER$\nu$A collaborators to help "translate" the code. Additional time would be required to update the production code that manipulates Gaudi options files to define jobs. The "fickle" files used by art are quite similar so this task may not be so serious.

- DAQ support. While we are changing offline frameworks, it could make sense to shift the MINER$\nu$A DAQ to use artdaq as well instead of ET for event transfer and buffering, etc. This is dependent on the overall online support model for CAPTAIN-MINER$\nu$A. Using artdaq for MINER$\nu$A could improve the overall long-term support model for Fermilab as it brings the core technology more in-line with local expertise.

- Near-online support. Should the MINER$\nu$A DAQ transition to using artdaq and art, the "Near-online" (monitoring) software would also need to be updated. Since CAPTAIN is using a version of artdaq, this would provide an opportunity to integrate the event displays and detector health monitoring systems into one integrated package that would make operating both detectors at once by one collaborator much simpler. This is a non-trivial change, but it is worth pursuing as it would bring all the components of the MINER$\nu$A DAQ in compliance with supported software at Fermilab.

# 9 Collaboration Management

The physics goals described in this proposal are of interest to both the current CAPTAIN and MINER$\nu$A collaborations, and the effort needed to achieve these goals is larger than either current collaboration could supply. Therefore we plan for members of each of the two current collaborations to join together as one new collaboration, and the data taken by both detectors (and the MINOS ND) would be readily accessible to all members of the new collaboration. For the moment this new experiment is called CAPTAIN-MINER$\nu$A. The author list of this document represents the current members of both collaborations who expect to contribute to the CAPTAIN-MINER$\nu$A experiment, including 61 CAPTAIN collaborators from 15 institutions and 66 MINER$\nu$A collaborators from 15 institutions.

Similarly, the reconstruction of events would have to combine information from up to three detectors, in addition to the neutrino beamline information, therefore the reconstruction software for all three detectors needs to be shared throughout the entire collaboration.

This new collaboration would make use of existing infrastructure from the current MINER$\nu$A and CAPTAIN experiments (document data bases, simulation packages, etc) until such time that it makes sense to merge that infrastructure into one new platform.

# 10 Program Schedule and Relation to CAPTAIN-BNB

The start date for the CAPTAIN-MINER$\nu$A project depends on several factors. The first is the availability of the CAPTAIN detector. The earliest date that CAPTAIN could be moved to Fermilab is in the Fall of 2016.

A separate LOI has been submitted [4] to place CAPTAIN in an off-axis position in the BNB at Fermilab to study neutrino-argon interactions in the few tens of MeV energy region, important for detection of supernova bursts in DUNE. A new building would be constructed near the BNB target hall to hold the CAPTAIN detector. Ideally, we would like to run both CAPTAIN-MINER$\nu$A and CAPTAIN-BNB on a time scale such that they can both provide useful input for DUNE.

One critical factor for the schedule is the availability of the NuMI beam. Our understanding is that both the NuMI beam and the BNB will operate until at least 2021 (NuMI for the NO$\nu$Aexperiment and BNB for MicroBooNE and other short-baseline neutrino projects). Assuming CAPTAIN is moved to Fermilab in 2016, we can expect at minimum five years to complete both the CAPTAIN-MINER$\nu$A and CAPTAIN-BNB programs based only on beam availability.

Since NuMI is expected to be running for a sufficient amount of time, a more important factor for CAPTAIN-MINER$\nu$A's schedule is the availability of the MINER$\nu$A detector and collaboration. The MINER$\nu$A collaboration expects to stop operating MINER$\nu$A and the MINOS ND after accumulating $12 \times 10^{20}$ POT in antineutrino mode and $6 \times 10^{20}$ POT in neutrino mode. When this occurs depends on the NuMI run plan and accelerator and beamline performance, but could be as early as 2018. The CAPTAIN-MINER$\nu$A project depends critically on the participation of the MINER$\nu$A collaboration in installing the detector, operating the detector, and analyzing the combined data set. Therefore, CAPTAIN-MINER$\nu$A data collection should begin by 2018 at the latest. After that date, there likely would not be enough participation from MINER$\nu$A collaborators for CAPTAIN-MINER$\nu$A to be feasible.

The start date of the CAPTAIN-MINER$\nu$A and CAPTAIN-BNB programs both depend on the installation of necessary infrastructure at Fermilab. The infrastructure required for CAPTAIN-MINER$\nu$A has been described in previous sections, and we estimate the work will take approximately 15 months. Many of those tasks (design and ODH calculations, for example) can be completed before the CAPTAIN detector arrives at Fermilab. For CAPTAIN-BNB to run, neutron measurements must be made to determine the exact location and necessary shielding for the CAPTAIN-BNB structure. Those measurements are planned to be conducted by the SciBath collaboration in Summer 2015, before the summer shutdown of the BNB. With the results of these measurements, we expect a full proposal for CAPTAIN-BNB including a technically-driven schedule can be submitted to the PAC for the Fall 2015 PAC meeting. Once the technically-driven schedules for both CAPTAIN-MINER$\nu$A and CAPTAIN-BNB are well understood, we can decide which program should run first, based on physics priorities, technical considerations, and availability of people. While this does introduce some amount of uncertainty, we believe that delaying the engineering work for CAPTAIN-MINER$\nu$A until this decision can be made would be detrimental to both programs. We therefore request that the engineering resources necessary for CAPTAIN-MINER$\nu$A be provided on the assumption that CAPTAIN-MINER$\nu$A will run first. As shown in Figures 14 and 15, assuming the engineering work begins in October 2015, CAPTAIN-MINER$\nu$A could begin taking data by the end of 2016. This plan may be later modified based on the CAPTAIN-BNB technical schedule, but a final decision on the order of the two programs can likely be made by early 2016.

Any of the dates given in this section could change depending on a number of factors, including: changes in the NuMI or BNB schedules, a change in MINER$\nu$A's expected end date, a delay in CAPTAIN's move to Fermilab, a delay in the construction of the CAPTAIN-BNB building, or a delay in systems necessary to operate CAPTAIN in the MINOS near hall.

# 11 Summary

In summary, this paper presents a joint proposal from the CAPTAIN and MINER$\nu$A collaborations to study neutrino-argon cross-sections and event reconstruction in liquid argon in the neutrino energy range of 1-10 GeV. CAPTAIN-MINER$\nu$A would take data for at least 2 years, beginning no earlier than 2016 and no later than 2018. To meet this proposed schedule, the necessary preparations for the MINOS ND hall would need to begin in 2015. CAPTAIN and MINER$\nu$A share the goals of studying neutrino and antineutrino interactions that are important for the future long-baseline neutrino oscillation program, and combining the CAPTAIN and MINER$\nu$A detectors will expand the physics reach of both experiments in a way that is complementary to existing liquid argon detector R&D efforts.

# A Appendix A: CryoRefrigerator quote and information

This section includes the information received from a potential vendor for the cryocooler that will be used to maintain the liquid argon in the CAPTAIN detector.

**CRYOMECH**

## Cryorefrigerator Specification Sheet

### AL600 with CP1114

| | |
|---|---|
| Cold head | AL600 |
| Cooling capacities (60 Hz*) | 350W @ 50K 430W @ 60K |
| *reduced capacities @ 50 Hz | 510W @ 70K 600W @ 80K |
| Lowest temperature | 25K with no load |
| Cool down time | 15 minutes to 80K |
| Weight | 92 lb (41.8 kg) |
| Dimensions | See cold head line drawing |
| Compressor package | CP1114, available as water cooled only |
| Weight | 470 lb (213 kg) |
| Dimensions - L x W x H | 24 x 24 x 31 in (61 x 61 x 79 cm) |
| Electrical rating | 440/480VAC, 3Ph, 60Hz // 380/415VAC, 3Ph, 50Hz |
| Power consumption @ steady state | 12.5kW // 11.5 kW |
| Cooling water flow rate | Minimum flow 3 GPM (11.4 LPM) @ 80°F (27°C) maximum temperature |
| Flexible lines | |
| Standard length | 10 ft (3 m) |
| Weight per pair | 15 lb (6.8 kg) |
| System parameters | |
| Helium pressure | 230 ± 5 PSIG (15.9 ± .34 bar) @ 60 Hz<br>250 ± 5 PSIG (17.2 ± .34 bar) @ 50 Hz |
| Ambient temperature range | 45°F to 100°F (7 to 38°C) |
| Maximum sound level | |
| Water cooled | 76 dBA @ 1 meter |
| Shipping crate | Wood box |
| Weight | 730 lb (331 kg) |
| Dimensions - L x W x H | 48 x 40 x 59 in (122 x 102 x 150 cm) |

113 Falso Drive, Syracuse, NY 13211 USA
315.455.2555 v 315.455.2544 f cryosales@cryomech.com www.cryomech.com

Specifications subject to change without notice. Revised 26Oct12

Figure 16: Specifications for cryorefrigerator.

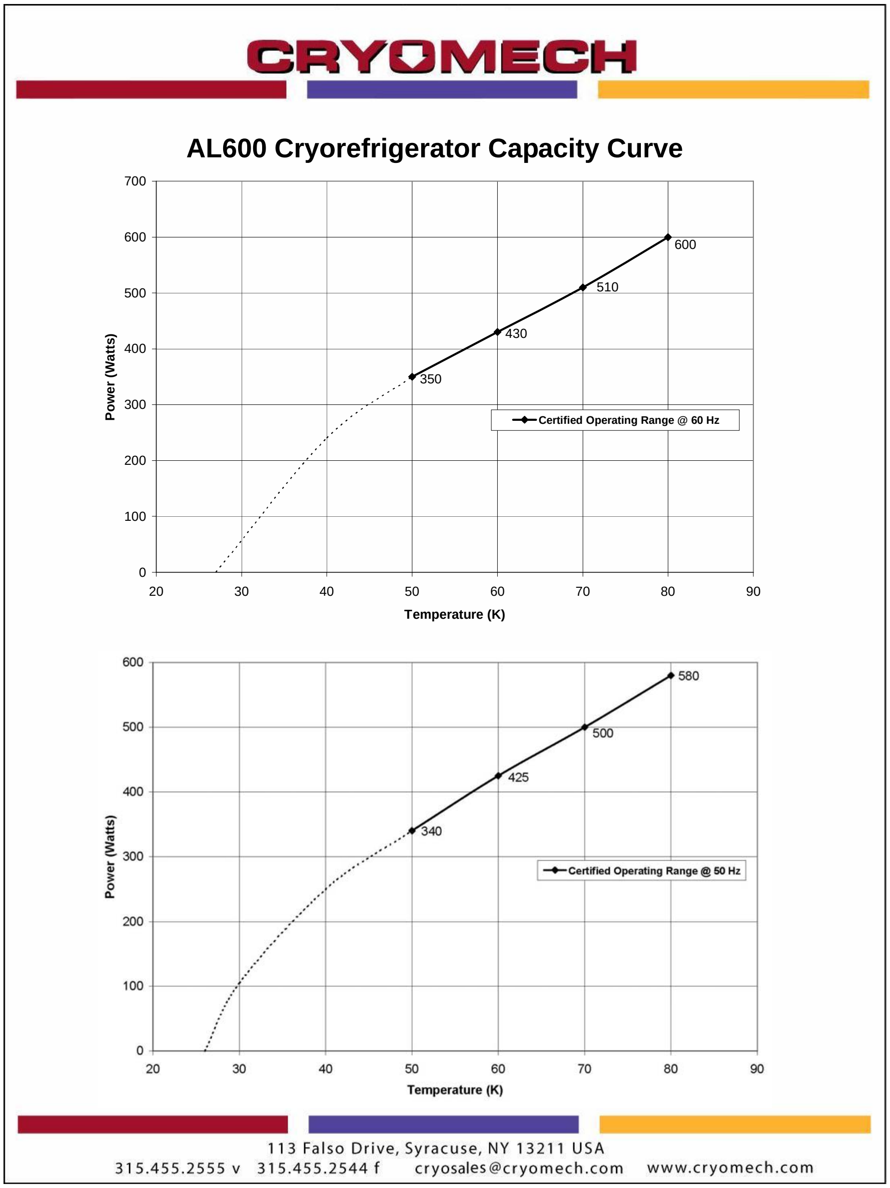



Figure 17: Capacity curve for the proposed cryorefrigerator.

**CRYOMECH**

113 Falso Drive - Syracuse, NY 13211 - USA
TEL: 315.455.2555 FAX: 315.455.2544 EMAIL: cryosales@cryomech.com

**Quote No: 1502190C**
Date: 2/19/2015
Page 1 of 1

| | |
|---|---|
| To: | James Kilmer<br>Fermilab<br>PO Box 500<br>Batavia, IL 60510 |
| Tel: | 630-840-2637 |
| Fax: | 630-840-3694 |
| E-mail: | kilmer@fnal.gov |
| COUNTRY OF OPERATION: | USA |

| | |
|---|---|
| PREPARED BY: | Katherine Applebee<br>Sales/Customer Service Representative |
| TERMS: | Net 30 |
| LEAD TIME: | **16 Weeks after receipt of order** |
| SHIP COMMENTS: | If more than one system is ordered, each subsequent system will ship in two week intervals |
| VALID FOR: | 90 Days |
| REF: | |

**Order Instructions**

**Please write the above QUOTE NUMBER on your written order**
**Please email order to cryosales@cryomech.com**
**The ship date offered on this quotation is an approximation of the production time under standard conditions**
**A firm ship date will be given upon receipt of your order**
**If you require a specific ship date, please provide us with this information**

**AL600 Cryocooler**

| Description | Part Number | List Price |
|---|---|---|
| **AL600 Cold Head** | **CH1A600** | $57,330.00 |
| **Helium Compressor Package (Available as Water Cooled Only)** | | |
| CP1114, Water Cooled, 440/480VAC; 3 Ph; 60 Hz | **CP1114W1LP** | |
| **Stainless Steel Flexible Lines** | | |
| 3/4" ID, Low Noise, 3/4" Aeroquip both ends, 60 Ft. Long | **TBD** | $1,350.00 |
| 1" ID, Low Noise, 3/4" Aeroquip both ends, 60 Ft. Long | **TBD** | $1,600.00 |
| **Cold Head Motor Cord, 60 Ft. Long** | **MC-6806-60** | $200.00 |
| **Installation and Operation Manual** | **IMC015** | |
| **Installation Tool Kit** | **ITK004** | |

| | |
|---|---|
| Total Cost of Goods | $60,480.00 |
| Packing/ Handling/ Documentation | $750.00 |
| Total FCA 113 Falso Drive Syracuse NY 13211 USA (2010 Incoterms) | $61,230.00 |
| Total (3) FCA 113 Falso Drive Syracuse NY 13211 USA (2010 Incoterms) | $183,690.00 |

*Important: Cryomech cannot be bound to revisions to customer orders received via an email message. All changes to customer orders must be accompanied by a purchase order and be confirmed by an order acknowledgement. Please note some revisions may result in addtional costs. Thank you.*

Figure 18: Quotation for the three cryorefrigerators that would be needed to operate the CAPTAIN detector (including one spare).

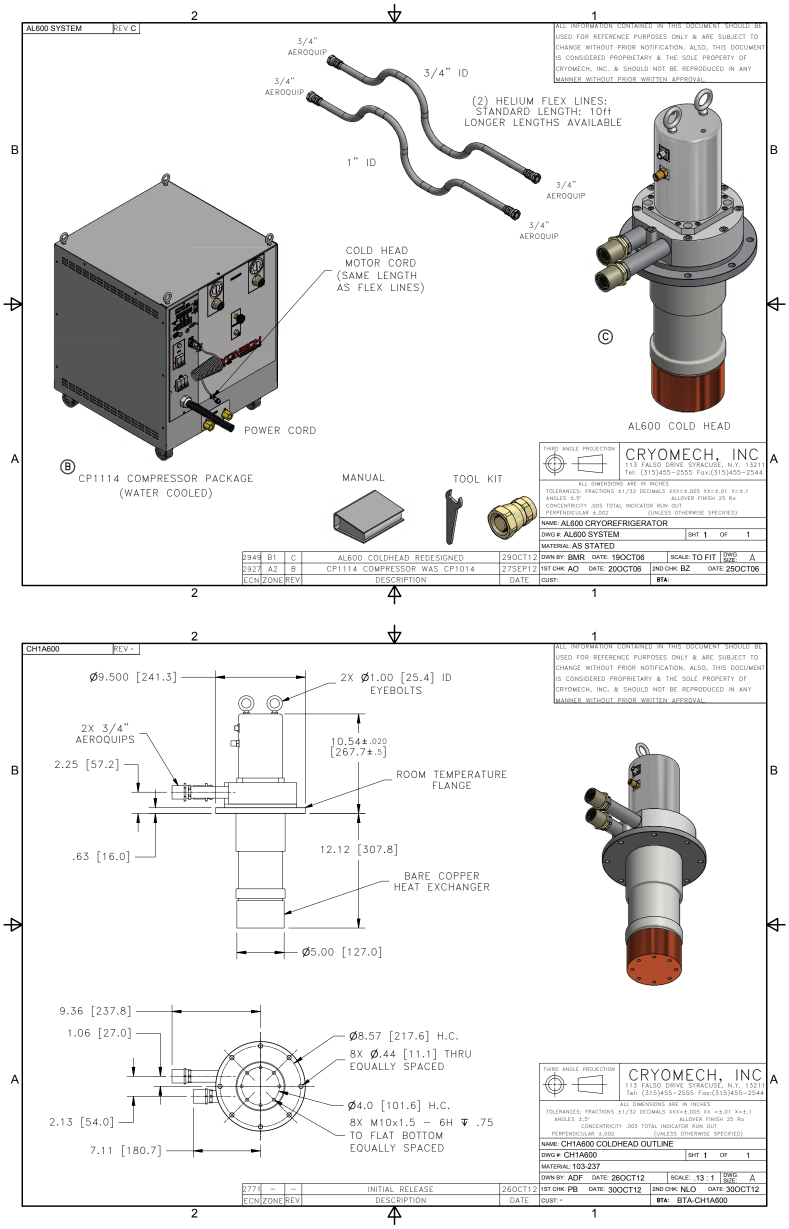



Figure 19: Engineering drawing for the cryorefrigerator that could be used to operate the CAPTAIN detector underground.

# B Appendix B: Controls Equipment and Labor Costs

***Process (Slow) Control System Cost Estimate*** Ver 1.0.0 DM 4/6/15

Estimate basis is flow diagram included in this proposal

| **Description** | **Unit Cost** | **Qty** | **SubTotal** | |
|---|---|---|---|---|
| **PLC Beckhoff (Master Programmable Logic Controller)** | | | | |
| Analog Modules | 230 | 20 | 4600 | |
| Discrete Modules | 70 | 10 | 700 | |
| Communications Modules | 250 | 3 | 750 | |
| | 0 | 0 | 0 | |
| | 0 | 0 | 0 | |
| | | **SubTotal** | 6050 | |
| | | | **SubTotal** | 6050 |
| **HMI (Human Machine Interface)** | | | | |
| iFIX Full SCADA ***2*** | 11530 | 0 | 0 | |
| PC's | 2000 | 0 | 0 | |
| iHistorian 500 pt | 7700 | 0 | 0 | |
| | | | **SubTotal** | 0 |
| **Instruments** | | | | |
| Pt Minco RTD | 25 | 0 | 0 | |
| Setra Transmitter C207 | 250 | 0 | 0 | |
| Fuji PSI Transmitter | 1200 | 0 | 0 | |
| Fuji DP Transmitter | 1200 | 0 | 0 | |
| Block & Bleed Mainfold | 200 | 0 | 0 | |
| Pt RTD Probes | 100 | 0 | 0 | |
| AMI Level Probes | | | | |
| Probe 8' Flanged | 1500 | 1 | 1500 | |
| Readout 185 4-20mA Output | 1000 | 1 | 1000 | |
| Vacuum Multi Range ATM to 10-10 Torr | 1000 | 0 | 0 | |
| Vacuum micron range | 370 | 4 | 1480 | |
| | | | **SubTotal** | 3980 |
| **Purity Analyzer Systems** | | | | |
| Purity Hi Quality | | | | |
| H2O Analyzer | 28000 | 0 | 0 | |
| O2 Analyzer | 30000 | 0 | 0 | |
| N2 Analyzer | 24000 | 0 | 0 | |
| Purity Lo Quality | 6000 | 0 | 0 | |
| Valves/Manifolds | 3000 | 0 | 0 | |
| | | | **SubTotal** | 0 |
| **Valve Actuators** | | | | |
| Badger Analog 1" | 1200 | 0 | 0 | |
| Fisher Analog (PHPK 1") ***3*** | 2700 | 0 | 0 | |
| Fisher Open/Close (PHPK 1") ***3*** | 1200 | 0 | 0 | |
| Fisher Analog (PHPK 2") ***3*** | 3300 | 0 | 0 | |
| Other-Emergency ShutOff PHPK2" ***3*** | 1800 | 0 | 0 | |
| | | | **SubTotal** | 0 |
| **Power/UPS** | | | | |
| Powerware UPS | 2000 | 1 | 2000 | |
| Load Center(Breaker Panel) | 3000 | 0 | 0 | |
| Generator (Backup, NG, 20KW, 480,3ph) ***4*** | | | | |
| | | | **SubTotal** | 2000 |

Figure 20: Partial list of parts needed for controls system for CAPTAIN

| | | | | |
|---|---|---|---|---|
| **ODH** | | | | |
| Fan x 5HP ***10*** | | | | |
| ODH Siren/Light | 400 | 3 | 1200 | |
| ODH Heads | 1000 | 2 | 2000 | |
| ODH Electronics | 500 | 2 | 1000 | |
| | | | **SubTotal** | 4200 |
| **Infrastructure** | | | | |
| Cable | 400 | 6 | 2400 | |
| Connectors | 1000 | 1 | 1000 | |
| Boxes | 1000 | 1 | 1000 | |
| Enclosures | 1000 | 1 | 1000 | |
| Racks | 1000 | 1 | 1000 | |
| | | | **Subtotal** | 6400 |
| **Motor Controls *5*** | | | | |
| VFD Pump motor controls | 2000 | 1 | 2000 | |
| | | | **SubTotal** | 2000 |
| **Heater Controls 9** | | | | |
| HTR Controls | 500 | 4 | 2000 | |
| | | | **SubTotal** | 2000 |

1 Assumes CPU Hot Backup for the Programmable Logic Controller.
Sized for 48 RTD, 32 AI, 32 AO, 32 DI, 32 DO.
2 Assumes SCADA Redundancy.
3 Assumes no options such as Hand Wheel. Min Air Supply 40 PSIG.
4 Backup Generator included due to Contamination risk and ODH ventilation during power loss.
Removed--Transferred to FESS and Building Costs
5 Assumes individual motor control cabinet instead of centralized MCC station.
6 VFD included in pump quote, not in this estimate.
7 This compressor requires local skid sensors and logic for interlock protection and operation.
8 Combined (3KW + 3KW) 6 KW sized to heat 80,000 lbs of stainless
from 70F to 140F in 32 hrs
9 Heater cost not included. No Specs available at time of this estimate
10 Removed--Transferred to FESS and Building Costs

Figure 21: Remaining list of parts and costs needed for controls system for CAPTAIN.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| ***CAPTAIN CRYOGENIC SYSTEM*** | | | | | | | |
| ***Automation Effort Estimate for known Project*** | **ENGINEER** | **TECHNICAL** | **PC ADMIN** | **DRAFTER** | **CALIBRATION** | **ELECTRICIAN** | |
| *Edited April 10,2015 by Dan Markley* **V1.0.0** | **MDAYS** | **MDAYS** | **MDAYS** | **MDAYS** | **MDAYS** | **MDAYS** | |
| **SECTION I** | | | | | | | |
| **Captain Cryogenic System** | | | | | | | |
| **1** Automation | **15.0** | **9.0** | **1.0** | **5.0** | **0.0** | **0.0** | |
| System Architecture/Wiring Plan | 5.0 | 2.0 | 1.0 | 5.0 | ( | ( | *13.00* |
| Logic Organization/Instrument List | 5.0 | 5.0 | ( | ( | ( | ( | *10.00* |
| Spec and Purchase equipment | 5.0 | 2.0 | ( | ( | ( | ( | *7.00* |
| **2** Hardware | **18.0** | **41.0** | **0.0** | **8.5** | **9.0** | **9.0** | |
| Dismantle Minerva System | 2.0 | 3.0 | ( | ( | ( | 1.0 | *6.00* |
| Premisis and power wiring for equipment | 1.0 | 2.0 | ( | 1.0 | ( | 2.0 | *6.00* |
| Tray/Trough/Cable Pulls | 1.0 | 2.0 | ( | 1.0 | ( | 2.0 | *6.00* |
| Rack Protection | 1.0 | 1.0 | ( | ( | ( | ( | *2.00* |
| Field wire instruments | 3.0 | 15.0 | ( | 1.0 | 2.0 | ( | *21.00* |
| UPS system | 1.0 | 2.0 | ( | 0.5 | ( | 1.0 | *4.50* |
| ODH system | 2.0 | 4.0 | ( | 0.5 | 1.0 | 1.0 | *8.50* |
| LAr Pump | 1.00 | 2.00 | ( | 0.50 | 1.00 | ( | *4.50* |
| Fridge System | 2.00 | 2.00 | ( | 1.00 | 1.00 | 2.00 | *8.00* |
| Prewire and Mount Equipment/Enclosures/Cabinets | 1.00 | 5.00 | ( | 3.00 | 2.00 | ( | *11.00* |
| Instrument Checkout | 3.0 | 3.0 | ( | ( | 2.0 | ( | *8.00* |
| **3** Software | **13.0** | **29.0** | **12.0** | **0.0** | **0.0** | **0.0** | |
| PC SCADA Node | 2.0 | 2.0 | 2.0 | ( | ( | ( | *6.00* |
| PLC Programming | 2.0 | 10.0 | 2.0 | ( | ( | ( | *14.00* |
| PLC Serial Programming | ( | ( | ( | ( | ( | ( | *0.00* |
| iFIX development | 2.0 | 10.0 | 3.0 | ( | ( | ( | *15.00* |
| Database Development | 2.0 | 3.0 | 1.0 | ( | ( | ( | *6.00* |
| OPC driver development | 1.0 | 2.0 | 2.0 | ( | ( | ( | *5.00* |
| Historical Cofiguration | 2.0 | 1.0 | ( | ( | ( | ( | *3.00* |
| Data share with experimenters | 2.0 | 1.0 | 2.0 | ( | ( | ( | *5.00* |
| **4** Engineering/Safety Docs | **8.0** | **0.0** | **0.0** | **2.0** | **0.0** | **0.0** | |
| Engineering Docs | 4.0 | ( | ( | 1.0 | ( | ( | *5.00* |
| Safety Docs | 4.0 | ( | ( | 1.0 | ( | ( | *5.00* |
| **Totals** | **54.0** | **79.0** | **13.0** | **15.5** | **9.0** | **9.0** | **MDAYS** |
| **SECTION II** | 432.0 | 632.0 | 104.0 | 124.0 | 72.0 | 72.0 | hours |
| | 123.46 | 74.84 | 106.22 | 82.70 | 74.84 | 120.00 | Rate |
| | $53,334.72 | $47,298.88 | $11,046.88 | $10,254.80 | $5,388.48 | $8,640.00 | Total |
| | | | | | | 135963.8 | Total |

Figure 22: Labor estimate for developing the controls system for CAPTAIN.

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